



Topic
Science
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Biology

A New History of Life

Course Guidebook

Professor Stuart Sutherland
The University of British Columbia



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Professor Stuart Sutherland is a Senior Instructor in the Department of Earth, Ocean, and Atmospheric Sciences at The University of British Columbia (UBC). He attended the University of Plymouth in the southwest of England, where he received a degree in Geology in 1987. In 1992, he was awarded a Ph.D. from the University of Leicester for his studies on Silurian microfossils called chitinozoa. His thesis examined the distribution and taxonomy of these fossils and considered the enigmatic biological affinities of the group and their usefulness in paleoceanographic studies.

After receiving his Ph.D., Professor Sutherland took a temporary teaching position at Brunel University in west London, where he first realized that he had a passion for teaching geology and paleontology. In 1994, he started postdoctoral research at the Natural History Museum in London, working with other paleontologists in an attempt to understand the Devonian organic-walled microfossils of the Cantabrian Mountains of northern Spain. With his earlier teaching experience still in mind, he acquired a teaching degree from Sheffield Hallam University in 1995 while still working for the museum.

In 1998, Professor Sutherland emigrated to Canada and eventually secured a faculty position at UBC's Vancouver campus. His interests at UBC are diverse but in general center on Earth history and paleontology with a particular focus on teaching. He has received, on three separate occasions, the UBC Earth and Ocean Sciences Teaching Award. He also has received the Faculty of Science Teaching Award and the Killam Teaching Prize from UBC. Professor Sutherland has been mentioned as a "popular professor" among students in two editions of *Maclean's Guide to Canadian Universities*.

Professor Sutherland developed his lifelong fascination with rocks and fossils on family hikes in Derbyshire and the English Lake District. He now enjoys studying these features in the beautiful environment of Vancouver and British Columbia. ■

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A New History of Life

Scope:

Do you like history—perhaps investigating where your family came from or learning what challenges your ancestors met and where they called home? This course traces some of the wanderings of our wider family, the biosphere, from its first appearance on Earth around 4 billion years ago through to the present day. This journey has been a fantastic one, with many interesting twists and turns along the way, many high points and more than a few crises.

Understanding how such a complex body as our planet came into being and evolved over time is no small task. The Earth is no simple experiment running in a test tube in a well-controlled and documented laboratory; rather, it is composed of interrelated and complex systems that have been evolving and, in many cases, coevolving over time. In recent years, scientists have realized that to truly understand our planet today and in the distant past, we have to consider it as a whole, a machine composed of many parts. We called this viewpoint Earth system science, and it will form one of the themes running throughout this series.

But even if all the history of our planet had been documented in detail by some ancient race of alien beings, it would likely still be difficult to parse through all the information and fully comprehend how all the parts of the great “Earth machine” work.

We have a record, of course—a record of ancient and distant times preserved in the layers of rock that we find all around us. Like the pages of a book, these strata can be read with just a little understanding of geology and paleontology, tools you will gain through this series. Unlike our alien friends recording Earth’s history from the comfort of their spacecraft, however, we will have to work hard to unravel the ancient tales of Earth. Our story is present all over the planet, but parts of it are currently missing or possibly gone altogether. We will have to be detectives if we are going to piece together this drama.

The tools we need are basic but powerful. They include an understanding of how rocks are formed and laid down, an appreciation of the passage of geological time and how it is measured, and insights into how fossils form and the information they can provide, as well as an awareness of bias that could potentially creep in to our interpretations. We also need one more element in our investigations: a grand unifying theory of the geosciences, a theory that links much of the data we will gather. This theory is called plate tectonics, and it is another theme running through these lectures.

We will start by detailing Earth's history in the earliest times, well before life had made an appearance, even before the Earth had formed. This course will trace the Earth evolving from a cloud of dust and gas through to a ball of magma hanging in space. We will see how these distant events have profound implications for the evolution of life on Earth well before the first life form made its first appearance on our planet.

Research is showing that the young Earth was a violent and alien place and that our nearest neighbor, the Moon, would also be born in catastrophe. It, too, would have a vital role to play in nurturing and then protecting Earth's biosphere. How and from where that biosphere would emerge are still much debated, but it would appear that everywhere we look, from the depths of the oceans to the skies and further into the space, the stuff of life is abundant and available, just awaiting a nursery to start the whole process moving. We think life's story starts early. Perhaps as long as 4 billion years ago, our biosphere was already off the starting blocks and running. It is likely that there is an unbroken line in all our cells to those dim and distant times, but even at this point, our most remote ancestors may have had to survive the sterilization of the surface of the Earth—just one of many challenges to come.

Earth's earliest fossils are rare and precious things. Their interpretation can be difficult and controversial at times, but the dawning of Earth's life forms was a remarkable event in the history of our planet. Almost immediately, life started to have profound effects on the early Earth, altering the very chemistry of our atmosphere and possibly permitting the presence of liquid oceans when really the planet should have been encased in ice. The ice would come eventually, but it would be called into existence by the activity of life itself. The evolution of microbes performing new and complicated

tricks would start to radically alter the Earth system and drive the planet into a frozen state; this could have been a terminal experience for the biosphere but instead would spur it forward to greater complexity.

Even though our planet has a long history of life, the majority of that life has been microscopic. Following another pole-to-pole glaciation, creatures composed of multiple cells started to emerge. They would diversify suddenly and dramatically around 542 million years ago, creating a biosphere—no longer drifting passively in the oceans or forming mats in shallow water. Instead, life would actively interact with the Earth, crawling over the ocean floor, swimming above it, and digging into it. The Earth would see a true flowering of life forms that would continue to diversify and expand into new parts of the Earth system.

Although biodiversity would steadily increase, at times in the history of the biosphere, the tree of life has been severely pruned. These times of crisis have occurred on several occasions over the last half billion years, including one event around 251 million years ago when the story of life almost came to a halt in and around the supercontinent called Pangaea. We will examine these mass extinction events and trace their causes to an interplay of mechanisms in the Earth system.

The biosphere would eventually conquer the land, first by plants and insects and then by our ancestors, the vertebrates. This course will trace the challenges that life faced to conquer this difficult environment. New and fascinating fossil evidence is coming to light regarding this exciting period of Earth's history, revealing some of the surprising and unexpected directions the biosphere would take in order to make that leap. We will follow the story of the vertebrates, tracing their origins in the explosion of life 542 million years ago through to their great leap onto the land. We will see how our branch of the story was almost lost before it began 251 million years ago and witness the emergence, flowering, and ultimate demise of the dinosaurs around 65 million years ago. The dinosaurian world would also see the vertebrates powering themselves into the sky, following other members of the biosphere who had made it there before them. The oceans would continue to evolve through this period and would witness the evolution of beautiful creatures at many scales, from the microscopic to the truly monstrous.

An unwelcome visitor from space would open up ecological space that would allow the evolution of new and beautiful creatures, this time dominated by the mammals. We will trace the movements of mammal communities across a world that was starting to resemble our own but was still populated by creatures that looked very strange. Toward the end of this series, we will document the events and the players in a part of life's story that would ultimately witness the dawning of consciousness in the Earth system—a part of the biosphere, a part of the universe, that would look back through time and consider its origins and perhaps contemplate the possibility of striking out from its nursery and spreading Earth's biosphere across the stars. ■

The Interconnected Earth

Lecture 1

The study of paleontology opens doors to the deep past and uncovers ancient secrets that have long been hidden. It also provides lessons for the present and, perhaps more important, a window into the future. What's more, of all the sciences, paleontology and geology are the most narrative. They tell the story of our planet, written in the rocks. Think about strata—the layers of rock laid one on top of another. They are like the pages in a book; each of those rock strata contains information about an ancient Earth long since vanished. This course will provide you with some of the basic tools that will allow you to read that story for yourself.

Earth System Science

- In this lecture, we will look at the Earth as a complex system. Earth system science considers the interconnectedness of all aspects of Earth, which is the theme of *A New History of Life*.
- Earth system science divides the Earth into a number of spheres, or systems, which are then arranged in hierarchies. An example of a system is a tree leaf. The leaf is composed of plant cells, and each plant cell is itself a system composed of many integrated parts. What's more, the leaf isn't isolated; it's actually attached by a stem to a branch and, of course, to the larger tree. The tree is part of the forest; the forest is part of a wider ecosystem.
- What we're trying to do is to understand things in a greater context. For example, it is not enough to understand what a fossil looks like and what its shape and form are; we need to understand what this creature did when it was alive. It is so much more than a long Latin name and an age. We need to read it in the context of the Earth system that it originally inhabited.

The Four Systems of Earth

- What are our Earth's major systems, and how are they classified?

- The lithosphere, sometimes called the geosphere, is all the rocky material that we are walking around on.
- The hydrosphere is all the water on the planet, whether in lakes, rivers, oceans, or groundwater. Some scientists also split off a category of the hydrosphere called the cryosphere to account for all the frozen water on the planet.
- The atmosphere is the thin layer of gases that surrounds the surface of our planet.
- The biosphere represents all the life that not only covers the surface but also penetrates quite a way into the geosphere and up into the atmosphere.
- All major Earth systems are open systems. For example, the ocean, a major open system, receives both matter and energy from other systems—for example, the atmosphere. Rain can fall into the ocean, and water can effectively be evaporated away to form clouds in the atmosphere. Oceans can heat up and get cold, as well; they can exchange energy.
- The entire Earth, however, is a closed system, although not a perfect one; there is some leakage of matter out of the atmosphere. But in terms of exchange, it is mostly energy: sunlight coming into the Earth, the heat radiating out, and losing that heat to space.

Hierarchy of Systems

- Now let's turn to the hierarchy of systems and the orders of complexity they demonstrate. Starting with a molecule, we can see that a molecule is part of larger molecules and macromolecules—for example, DNA.
- DNA itself is a component part of small systems of cells that we call organelles—for example, mitochondria, which are the powerhouses of the cells. Mitochondria are like micro-machines within a cell system. A cell system forms tissue systems composed

of many cells. Tissues make up organs. Organs themselves are part of a wider system; for example, the stomach is part of the digestive system. The digestive system is one of many systems in the body, including the reproductive system and the nervous system, that all go together to combine to form the highest level of this system, which is the human organism.

- Systems hierarchy is interesting in that it mirrors the evolution of systems from simple (molecules) to complex (organism). For example, simple molecules can represent the state of the Earth very early in its history. Once the Earth had cooled, there were pools of water full of organic molecules. Eventually, those molecules got together to form macromolecules and, ultimately, the first cells, about 4 billion years ago. Then, associations of cells formed the first simple algae. Ultimately, about 600 million years ago, complex organisms formed.

Importance of Feedback Loops

- How are systems related to each other and how do they interact? Interactions in Earth systems science are controlled by what are called feedback loops. Feedback is a very important concept in systems theory. Feedback drives systems into or out of stability. There are two kinds of feedback: negative and positive.
- An example of a negative feedback system has been very much in the news: the greenhouse effect. Carbon dioxide allows (as does the rest of the atmosphere) solar radiation, or short-wave radiation, to



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Early in its history, Venus may have had liquid water oceans, but as the Sun became brighter and the surface of the planet became warmer, the oceans on Venus evaporated into its atmosphere.

penetrate to the surface. This radiation heats up the surface of the planet, and the planet then radiates long-wave radiation back into space. Some of that long-wave radiation, however, is absorbed by carbon dioxide molecules; in this way, the carbon dioxide acts like a blanket. It keeps the planet warm. The greenhouse effect, which has gotten some bad press, is not always such a bad thing. In fact, we need the greenhouse effect to keep our planet warm. It has been keeping our planet warm for billions of years.

- Although negative feedback stabilizes conditions in systems, positive feedback has the opposite effect. Positive feedback tends to drive systems into states of instability. As our planet warms, the cryosphere—the icy part of the atmosphere—starts to shrink. Ice has what we call high albedo, or reflective power: It is white. It reflects a lot of solar radiation. That reflected solar radiation goes into space, which keeps our planet cool; thus, the less ice we have, the less reflection and, therefore, the more heat absorbed. But once the ice is removed, surfaces are exposed—land and oceans—that actually look very dark from space. Dark surfaces absorb heat. We have a positive feedback loop operating here.

The Gaia Hypothesis

- On average, over the past 600 million years or so, our planet has been fairly well regulated. There have been no complete evaporation events. The oceans have not disappeared into the atmosphere, nor has ice rumbled down from the poles to meet at the equator. We think that Earth's feedback mechanisms have maintained this homeostasis. In a way, the Earth could almost be regarded as self-regulating.
- This is an idea that was popularized by James Lovelock, who viewed the Earth as a very large, self-regulating organism. He called this the Gaia hypothesis. Gaia is a Greek goddess who personified the Earth. Lovelock maintained that the Earth's homeostatic state is really just the result of many complex feedback mechanisms operating together.

- To demonstrate how Gaia could self-regulate just using simple feedback, Lovelock created a thought experiment. Imagine a planet that has two kinds of daisies: dark daisies and light daisies. The light daisies, with high albedo, reflect heat, like the ice described earlier. The dark daisies, of course, absorb heat.
- This daisy world orbits a sun like ours that initially was not as bright. Like our Sun, it was 30 percent less luminous. And, at those times early in the history of this world, the daisies can inhabit equatorial regions only because those areas receive maximum sunlight and are the warmest. After the first generation, dark daisies will have selective advantage. They are dark and can absorb more heat; the planet starts to heat up, and the dark daisies, as a result, spread, absorbing more heat—which allows for the spread of more daisies. We are into a positive feedback loop here. The result at the end of this first stage is that the planet will be warmer than expected if life had not be present.
- Time moves on, the sun gets brighter, and the temperature increases. Now, it becomes too hot for dark daisies at the equator, and the white daisies have the selective advantage because they can reflect the sunlight back and keep those equatorial regions cooler. This is a negative feedback loop that has been initiated. Planet temperatures are starting to be regulated. We are moving into a homeostatic state. The sun eventually reaches a mature state, and some sort of equilibrium is reached.
- Whether you buy into Lovelock's idea of a self-regulating Earth system is not the point, however. What is important is an appreciation that the Earth is composed of many systems—the major ones being the hydrosphere, atmosphere, geosphere, and biosphere. Changes in one or the components of one will have domino effects on all the others.
- To understand how Earth systems have evolved over time, we need an appreciation of an incredibly important concept in the geosciences—one that is relatively recent. It is the concept of deep

geological time, which allows some incredible events to happen in the history of the planet. We will examine those in the next lecture.

Suggested Reading

Lovelock, *The Ages of Gaia*.

_____, Personal website.

Skinner, Porter, and Botkin, *The Blue Planet*.

Questions to Consider

1. Is Earth system science really a new paradigm or is it just a way of making old ideas appear new by the generation of a new set of jargon?
2. Is it possible that the broad view of inquiry presented by Earth system science, rather than helping understand our planet, runs the risk of removing critical focus on specific issues?

The Vast Depths of Earth Time

Lecture 2

This lecture deals with the evolution of Earth's integrated systems over deep geological time. We will see how we can tell the story of the Earth by looking at rock layers. For example, there is a vast history recorded in the Grand Canyon in all those layers of rock; this lecture will give you the tools you need to understand and read that narrative in the rocks.

Calculating the Age of Earth

- Archbishop James Ussher was one of the first people to try to calculate the age of the Earth. Using the Bible, he added up all the dates that were recorded to provide a timeline and came up with a date for the first day of creation, October 22, 4004 B.C., making the Earth just a little more than 6000 years old.
- However, many scientists believed that 6000 years did not seem long enough; there was too much happening in the rock layers they were looking at. A scientist named James Hutton had another way of determining geological time. His findings in geology would revolutionize the discipline.
- Hutton built on the geological principles of an earlier scientist, Danish anatomist and geologist Nicolas Steno. Steno developed the principles of stratigraphy, the science of how rock layers are laid down and how they are arranged in various combinations. Stratigraphy is the basis of our understanding of geological time.

Principles of Stratigraphy

- Steno's first principle of stratigraphy is that of superposition. It states that a section of rock reflects processes in which layers have developed on top of other layers over time. Basically, it means that the layers at the bottom of a section are the oldest, and the layers at the top are the youngest.

- You may have seen rock layers that are tilted or folded into complex shapes. Steno's principle of original horizontality states that rocks that were originally sediments laid down in oceans, lakes, or lava flows would not have been deposited at an angle; they would have been deposited flat and would have been tilted after they had turned into rock. Again, this implies a history to the rock layer; it has gone through a process.
- Hutton brought another concept to these basic principles—that of cross-cutting relationships. Think of the rock layers you see that are horizontal in nature, but running diagonally across them are darker rocks that cross-cut those horizontal strata. That darker area, the diagonal stratum, is called an igneous dike, and originally, it was hot magma that forced its way through those sedimentary rocks. It later cooled to form the rock that we see today. From that, we can make a rather simple but very profound deduction: The igneous dike must be younger than the sediments that it cross-cuts.
- An important moment for Hutton occurred in Siccar Point in Scotland—like the Grand Canyon, a holy place for geologists. There, you can see vertical strata, or strata that have been turned up on their end. When you examine these rocks, you can tell that they were deposited in a deep ocean during the Silurian period, about 425 million years ago. Other rocks, however, were actually deposited in a completely different environment—not in a deep ocean but in a desert during a period called the Devonian, about 345 million years ago. That hiatus, a period of non-deposition, is called an unconformity.
- To Hutton, it was amazing to think that in one area in Scotland was evidence of both a deep ocean and an arid desert. There was one important factor needed to explain that: time—a great deal of it.

Evolution of Fossils

- The idea of an ancient Earth would be popularized by many scientists, including Charles Lyell, a uniformitarian. Hiking around Mt. Etna in Sicily, he noticed fossil-rich rock: fossiliferous



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From his observations of parasitic cones on Mt. Etna—that is, smaller volcanoes that develop on the back of a larger volcano—Charles Lyell concluded that Etna itself must be millions of years old.

limestone. When Lyell examined the rock, he noticed that the species he was identifying in it were not really all that different from species that could be found around the Italian coastline in the present day; thus, this rock could not really be all that ancient.

- However, when he traced this limestone, Lyell found that he passed across a plain and then passed underneath Mt. Etna. Mt. Etna was eroded through and built up over the limestone. Using the principle of cross-cutting relationships, that must mean that Mt. Etna is younger than the limestone; therefore, the fossils must be millions of years old, too. If fossils millions of years old are the same as living species, then the rate of appearance of new species must be incredibly slow. To progress from the ancient fossils to the current biosphere must require vast amounts of geological time.
- Today, rather than uniformitarianism, we use the term “actualism.” Uniformitarianism implies that the Earth processes are extremely

slow, such as the erosion of mountains by streams. Although actualism acknowledges the slowness of processes, it notes that occasionally, there are also sudden, dramatic, and catastrophic events, such as the eruption of a volcano or the impact of a meteorite from outer space. Geologically speaking, these are instantaneous events.

Relative Dating

- How do we provide actual dates for some of the events in Earth's history? So far, what we have described is relative dating, which works out the relative order of events and determines what is older or younger than something else.
- For example, trilobites are always going to be found below certain other fossils, such as ammonites. We know that trilobites are more ancient than ammonites. That is a relative dating technique.
- Or, for example, imagine that you wanted to record how quickly muddy sediments are accumulating in an ocean or a lake. Say you worked out that the rate was about 10 feet per million years; therefore, 100 feet of mudstone must represent 10 million years of geological time. However, inherent errors are built into this system; we are assuming that the accumulation rate of sediment is constant. This provides only a very rough estimate of geological time.

Absolute Dating

- A much more precise method is needed—an absolute dating technique—to supplement our relative dating techniques. That absolute technique is called radiometric or radioactive dating. It is based on the understanding of radioactive decay, and it proceeds on the fact that certain elements exist in different forms, called isotopes.
- Carbon has three naturally occurring isotopes: carbon-12, carbon-13, and carbon-14. Carbon-14 is an unstable isotope, which means it decays. When it decays, it gives off radiation and forms a more stable compound—in this case, nitrogen-14. This rate of

decay can be determined experimentally; therefore, the ratio of the unstable parent isotope to the stable daughter element can be used to determine the amount of time a certain substance has been decaying. We have our ticking geological clock.

- Although carbon-14 is useful for archaeological studies, it cannot be used geologically because it decays too quickly. But fortunately for the geologists, there are many other isotopes in rocks that we can use. A good example is uranium-238, which decays into lead-206. This decay is much slower, taking place over billions of years.

How Old Is the Earth?

- How old is the Earth? Unfortunately, the earliest parts of the story are lost to us. In the study of geology, the further you go back in geological time, the less evidence you find. If you want to look at evidence of sediments deposited in the last glacial period, there are lots of them all around the landscape. If you want to find rocks from the Cambrian period (about 400 to 540 million years ago), there are fewer of them. The reason is that our planet is highly active. The very earliest parts of Earth history have been recycled or eroded.
- Although those early parts of Earth's history have been lost on our planet, there is still some of the debris left over from the early formation of the solar system. For example, if we do a radiometric date of a meteorite, we come up with an astounding age of about 4.54 billion years old for the generation of the solar system—and for the generation of the Earth, as well.
- We'll close with a visualization of the vast depths of Earth time. Take all of Earth's history, 4.54 billion years, and condense it into one calendar year.
 - In that calendar year, the Earth forms on January 1; the oldest rock we have preserved today on the surface of our planet comes from about February 1. About July 25, we get the first oxygen in our atmosphere. On November 15, creatures with shells first appear. Life had appeared much earlier, but it is

not until this very late date that creatures really start to get substantial and possess skeletons or shells.

- By December 15, dinosaurs evolve, and by December 26, they are gone. The end of the last glacial period occurs on December 31 at 11:59:18, and the birth of Christ is December 31 at 11:59:46. Most of human recorded history occurs in the last seconds of this geological timescale.
- We know that the Earth is ancient. But if we are going to tell the story of the Earth, we need to keep tabs on all our Earth history. We need to know if the story of geological time is the same in Canada as in China. We need a correlation tool to tie the two areas together in time. For that, we are going to need fossils, which we will discuss in the next lecture.

Suggested Reading

Denby, “Northern Lights.”

Levin, *The Earth through Time*.

Questions to Consider

1. Do you think a proper understanding of our place in the vast history of our planet would have a sobering effect on the Earth’s leaders and politicians?
2. If you were living at the time of Charles Lyell, do you think you would find his ideas regarding the age of the Earth reasonable or preposterous?

Fossil Clocks

Lecture 3

In order to adequately read the story of the Earth, we need a tool that ensures that when we are talking about geological time, wherever we are in the world, we are on the same geological page. We have to make sure that the story is the same whether we are in Montana or Mongolia. The problem is one of correlation. Fossils can act as timepieces and can help solve the problem of correlation.

Igneous and Sedimentary Rocks

- It is not difficult to test the age of rocks using absolute radiometric dating. Using this method, we measure a ratio between the unstable parent element and stable daughter material. Ideally, to get the best results, we need an isolated, enclosed system.
- Fortunately, we have what is close to an isolated system naturally in igneous rocks—rocks that are crystallized from cooling magma. As those crystals grew when the magma was cooling, they trapped small amounts of radioactive parent material within their crystal structure—effectively isolating that material from the rest of the igneous rock. Within that isolated crystal system, the radioactive parent material can then decay into the daughter material. This gives us an isolated system, within which our geological clock is ticking.
- The problem here is that more than 75 percent of the rocks on the surface of our planet aren't igneous rocks but sedimentary. Sedimentary rocks contain the majority of the environmental and fossil evidence that we interpret to tell Earth's history. What we really need is to be able to date sedimentary rocks.
- Sedimentary sandstone is composed of rock that has been eroded from a preexisting rock, transported, and then deposited elsewhere. We do not see fine crystals; we see fragmented crystals or

fragmented parts of other rocks. Even if we were to find a complete crystal that had not been cracked open and contaminated, it really would not do us any good. If we were to date that crystal accurately, all it would tell us was the time of formation of the rock from which this sediment was derived. It wouldn't tell us when the sediment was deposited.

A Brief History of Fossil Theory

- Herodotus, a Greek philosopher, considered fossils representatives of formerly living organisms—which is the modern view. Leonardo da Vinci, who would commonly find fossils in rocks on the tops of mountains, was particularly interested in fossil clams. He concluded that fossil clams are evidence of former life that is now preserved in stone through some sort of process. He also concluded that the reason fossil seashells are found on mountaintops is that those seabeds had been raised to the level of the mountains. That was a fairly profound thought for someone in da Vinci's day.
- In 1666, a shark was caught near Livorno in Tuscany, and the head of that shark was sent to Nicolas Steno. Steno dissected it and realized that certain structures he had been studying that resembled stones were, in fact, fossil shark teeth. He realized that the ancient shark's teeth had changed from formal organic living things into nonliving things by a process—a process that we now know as fossilization.
- William Smith, who was born in 1796 in Oxfordshire, England, grew up surrounded by fossils. They were everywhere. Fossil sea urchins were commonly used at the time as weights on scales. In addition, brachiopods, which look a bit like clams, were used as marbles.
 - While working as a mine engineer and canal builder, Smith noticed that certain rock strata seemed to be characterized by certain groups of fossils. He realized that there was a regular order in the succession of these fossils, and that certain fossils always occurred stratigraphically above other fossils.

- This is the basis of what we call the principle of faunal succession. This principle is useful because if we find fossils in different rocks, and we know that certain groups of fossils characterize certain areas stratigraphically, we can match those groups of fossils, even if we cannot trace a stratigraphical horizon. If we find the same groups of fossils, even if they are separated by great distances, we can assume that they are of the same relative age. We have correlation.

The Fossil Range

- The science of biostratigraphy uses the range of life that has existed over geological time to help us correlate between vastly separated areas on the planet. Today, paleontologists use what is called a fossil range, which is the basis of how we correlate using fossils.
- If we are going to correlate using a fossil, it would help if that fossil had a very short range—in other words, if it came into existence, existed for a short period, and then went into extinction. It also helps if that fossil is not restricted to one particular area or one particular environment. We want it to be widespread if at all possible. It would also help if the fossils are relatively common and easy to identify.

The Ideal Fossil

- As we can see, the ideal fossil is not very easy to come by. Sometimes, we have to make compromises. For example, consider the graptolite. Graptolites were planktonic creatures that were very delicate. They floated around out in the ocean and existed in vast numbers. They evolved very rapidly, producing many short-range forms, and died and fell to the ocean floor, preserving many fossils. We use these for global correlation purposes.
- The problem is that when we get to sediments in shallower water, we do not find that many graptolites; they are too delicate. They tend to be smashed up. How do we correlate from sediments that represent deepwater environments to shallow-water environments?



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Trilobite fossils are used in conjunction with delicate graptolite fossils to correlate the age of sediments that represent deepwater environments to shallow-water environments.

- The answer is that we use trilobites. We find an area where the trilobites range geographically in the graptolites' range, and then we can progress from the biostratigraphic scheme of the graptolites into the biostratigraphic scheme of the trilobites. In that way, we can move around the globe, correlating from one group of creatures to the other.
- Other useful fossils for correlation are ammonites, which swam in the ocean and, therefore, existed in or above many different environments. Ammonites are particularly useful in subdividing the Mesozoic period, the time when dinosaurs were common.
- Less useful are bivalves, or clams, and gastropods, or snails. These are fascinating fossils, but they tend to be tied to the substrate in which they exist. They tend to live on the ocean floor, which means that they are not as widely distributed and not quite as useful for correlation. They are, though, good for identifying specific

environmental conditions; a particular gastropod will have a particular affinity for a particular environment and sediment.

Using Biostratigraphy

- Geological time today is policed, if you will, by the International Union of Geological Sciences (IUGS). This body determines how the geological timescale is split up and when a time division actually will occur. Time boundaries are also defined in space, through type sections. These are international reference sections where scientists can compare their particular rocks and fossils to a section that has been set up for correlation purposes. For example, the base of the geological period that we call the Silurian occurs at 443.7 million years ago, and the international reference section is at a place called Dob's Linn in Scotland.
- The Silurian period, as is the case with many geological periods, is defined by the first occurrence of a very distinctive fossil. In this case, it is the distinctive occurrence of a particular graptolite species, *Parakidograptus acuminatus*. As soon as we find *Parakidograptus acuminatus*, we have left the previous geological period, the Ordovician, and are in an entirely different geological period, the Silurian.
- With biostratigraphy, we have a benchmark that uses fossils for correlation. How do we add accurate dates to some of those sediments? Radiometric dating can help us. For example, in the Grand Canyon, where there is an igneous dike cross-cutting the sediments, we can date that igneous rock. The oldest sediments that the dike is cross-cutting must be older than the date we get from the igneous dike.
- But there are other things we can do, as well. For example, when a volcano erupts, it sends ash into the atmosphere. This ash can travel all around the world, which means that ash layers from volcanoes can be found many hundreds of miles from where they were originally produced.

- Ash also contains some of those important igneous crystals. We can find ash layers when we are looking at a whole pile of a sedimentary sequence. We call them bentonites, and they are a creamy color. Dating those ash layers gives us a date within that sedimentary pile. When we find successive volcanic eruptions, we can bracket sediments between them.
- Further, because volcanoes erupt very regularly (geologically speaking), we can produce lots of dates in these sedimentary sequences that we could not necessarily produce using radiometric dating.
- Our next lecture will continue to expand our understanding of fossils and demonstrate how the paleontologist acts as a modern-day detective.

Suggested Reading

Wicander and Monroe, *Historical Geology*.

Winchester, *The Map That Changed the World*.

Questions to Consider

1. Why do you think some people found it so difficult to accept that fossils were the remains of once-living organisms?
2. Is it possible that thinking of geological time in terms of rigid divisions gives a false impression of the passage of time on our planet?

Paleontologists as Detectives

Lecture 4

The paleontologist has very little evidence to go on when trying to reconstruct ancient worlds. Often, we are dealing with fragments of creatures or a geological record that is missing through erosion. Therefore, we must be very careful in interpreting past ecosystems. This lecture deals with these issues: how the paleontologist builds a picture of a fossil from fragmentary evidence, what defines a fossil species, how to use fossils to determine how ancient creatures interacted, and how to identify bias in our interpretation of the fossil record.

Using Comparative Anatomy and Models

- To make interpretations, paleontologists use paleobiology to determine what ancient creatures were like when they were alive—putting some flesh and bone onto them and considering their overall form and function, how they moved, and so on. Scientists also use paleoecology, which determines how ancient creatures interacted with their environment and with members of their own species and other species. And, using taphonomy, we can determine everything that happens to a creature after it dies and starts to decay up to the point where it may potentially become a fossil.
- Because there is so little information to go on, paleontologists have to act as detectives when interpreting ancient biospheres. One detective tool is called comparative anatomy. For example, say that a scientist finds a fossil leg, potentially a leg of a dinosaur. Many creatures today have legs, so we can compare the leg of the dinosaur to one of a living creature and generally work out how it functioned. We can look at the articulation of the bones. We can look at muscle scars and see how big the muscles were and how powerfully they contracted to get a good idea of how this dinosaur moved.
- Another tool we have is modeling. For example, consider the bizarre-looking fossil *Hallucigenia*. In one reconstruction, it has odd

spines as legs and tubes running down its back. Later discoveries of clearer specimens would literally turn this image upside down: It is now walking on those tube feet and has protective spines on its back. Paleobiology is all about making models and refining the hypotheses that we might form in the light of new discoveries and new evidence.

Interpreting Fossil Species

- Interpreting species paleontologically has direct implications for our understanding of diversity in the past. When we are looking at fossil species, we have to decide what particular group of fossils we are looking at. Are we looking at one species, or are we looking at many species (especially if they might look somewhat similar)?
- In paleontology, we use the morphological species concept. Basically, we just have to look at a species and make a determination, based on the structures that we can see, whether or not it is one species or perhaps one of many. This is problematic because the same species can look very different depending on a number of factors, such as developmental factors, environment, and gender.
 - Developmental factors include differences in size and proportion. Also, in some species, the young do not have skulls that are fully formed; the skull of a youth may be composed of more than one bone and may not be fused.
 - Environmental factors can cause variations in the same species. For example, consider the Inuit and the Masai. The Inuit live in cold conditions, so they have an adaptation for cold—to be more short and stocky to retain heat. Masai, however, live in hot climates, so there is an advantageous selection trait to be taller and thinner in order to lose heat more easily.
 - In the case of gender differences, males tend to be larger and have more robust bones because of their greater muscle mass. Females tend to be more gracile; also, the female's pelvis is adapted to allow for childbirth.

- There is much potential for a paleontologist to make mistakes—possibly to identify six different species when really there is just one species with differences caused by developmental, environmental, or gender factors.
- A recent example of species confusion in the paleontological world comes from a particularly famous dinosaur from the Cretaceous period, *Triceratops*. John Scannella and Jack Horner at the Museum of the Rockies recently suggested that in fact *Triceratops* did not really exist. What it represented was a juvenile form of another dinosaur, *Torosaurus*. Additional research may support splitting that species once again into two different species.



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Recently, paleontologists have suggested that *Triceratops* is actually a juvenile form of another dinosaur, *Torosaurus*, but additional research may invalidate that conclusion.

Using Paleoecology

- What can we tell from the fossil evidence about ancient creatures and how they interacted with one another? Types of interactions include mutualistic arrangements, commensalism, parasitism, and predation.
- We find an example of a mutualistic arrangement from the fossil record between a fossil sea snail called *Platyceras* and a crinoid, which is like a starfish on a long stalk. Very often, we find *Platyceras* right over the anal tube of the crinoid. What we think is that the snail is getting a free meal from the crinoid. It is removing its waste material, but the crinoid is also benefiting because it gets a cleaned-up environment in which to continue feeding.

- In commensalism, there is a definite positive benefit for one side of the arrangement and neither a positive nor a negative result for the other. An example from the fossil record is the fossil echinoid, or sea urchin. On its back are fossil tubes, probably from a worm that was making a home on the back of the echinoid. These tubes are not large enough to cause the echinoid any problems, but the worm is certainly getting benefits by having a hard substrate on which to live.
- A good example of parasitism in the fossil record is Sue, one of the largest and most complete *Tyrannosaurus rex* skeletons in the world. Sue has odd holes in the jaw—holes that were initially thought to be evidence of predation, but they did not seem to match any predation patterns. In fact, what they look most similar to are holes that we find in the feet and the mandibles of birds caused by a protozoan called *Trichomonas gallinae*. We believe that Sue got protozoans in her jaw, and they caused an infection, ulceration, and damage the bone, possibly fatally.
- Examples of predation include holes bored into a fossil shell—probably some sort of snail boring into a clam to get to the meal inside. Some holes in specimens have been interpreted as puncture marks. For example, some marks have been identified as those of the mosasaur, which was an apex predator, a terror of the Mesozoic oceans—specifically during the Cretaceous era.

How Are Fossils Preserved?

- A fossil is anything that reveals evidence of past life. Fossils can be preserved in a variety of ways. For example, we can find simple impressions of fossils, such as an impression of a shell that has been made into the sediment.
- Fossils can also be preserved through mineralization, or the replacement of the original organic material by other minerals. For example, in some cases, the original shell material of a brachiopod has been replaced atom for atom by another mineralizing media: iron pyrite, or fool's gold. But we can get replacement by other

minerals, including calcite, various iron minerals, and silica, as well.

- Freezing is another way to preserve fossils. For example, a baby woolly mammoth, about 40,000 years old, was recently identified. We can tell by looking at the lung content that it asphyxiated on mud. It was probably trying to cross some slightly swampy land; maybe permafrost had started to melt a little bit, and it got trapped and sank. The preservation is so good that we can actually open the gut and study this creature's last meal.

Biases in Reading the Fossil Record

- Not every creature has an equal chance of becoming a fossil; therefore, there are biases in the fossil record in terms of the potential for something to become a fossil. The science of taphonomy—studying the process of the death of a creature, to its complete decay, to the time when it becomes a fossil—can help ameliorate any potential biases.
- A potential bias in reading the fossil record is the environmental bias. Certain environments are more favorable to fossilization than others. Terrestrial environments, or land environments, are very poor. Creatures that live on land tend to lie on the open ground, and they are subject to scavengers. They will rot very readily and be eroded. In water, the record is better because creatures can be covered by sediment once they die. Because the oceans are so large, there is a definite bias toward marine fossils.
- Another bias is biological. For example, about 60 percent of marine organisms in today's oceans are actually soft-bodied. Obviously, the preservation potential for a soft-bodied creature is not as good as the preservation potential for something that has a more robust shell or skeleton.
- Paleontologists have to be careful of cultural bias when interpreting fossils, as well. An example is the *Iguanodon*, whose fossil was unveiled in 1854 at the Crystal Palace in London.

- This early reconstruction looks strange compared to our modern understanding of *Iguanodon*: There's a spike on its nose, while we now know that the spike on *Iguanodon* goes on the thumb.
- What we are looking at here is a kind of Victorian cultural bias. The Victorians thought reptiles were lesser creatures, not as good as mammals. Reptiles were sluggish, stupid, primitive, lumbering creatures and were depicted as such. Today, there is a much different view of these dinosaurs as active and dynamic creatures.
- Fossils are powerful tools as long as we interpret them carefully. The next lecture will discuss how a German meteorologist would start to use some fossils and, in doing so, turn the world of geology upside down.

Suggested Reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Foote and Miller, *Principles of Paleontology*.

Questions to Consider

1. Before you heard this lecture, what would you imagine that fossils could tell you about past “Earths”? After watching the lecture, has your faith in fossils as clues to the past increased or decreased?
2. When you were first exposed to fossils, what biases can you now understand might have been introduced by the materials or visual representations you were shown?

The Shifting Surface of Planet Earth

Lecture 5

Plate tectonics is the grand unifying theory of geology. It is based on the idea that the Earth's surface is not static; it is dynamic, continually moving. Plate tectonics explains all the major geologic phenomena that we see today and helps paleontologists understand changes in the deep geological past. This lecture will explore plate tectonics, the evidence that supports continental drift, why continental drift was originally rejected by the scientific community, and how the idea would ultimately be vindicated.

Early Theories of Continental Movement

- The theory of drifting continents is not a new idea. In the 1500s, Abraham Ortelius, a Flemish cartographer and geographer, published what is considered to be the first modern atlas. In studying the shape of the continents, he noticed the odd fit that one can make between South America and Africa. It is almost as if the two continents had been torn apart, he noted.
- Similar ideas were proposed by Antonio Snider-Pellegrini in 1858. He constructed a theory of a supercontinent that looks fairly similar to reconstructions made today. He based his reconstruction on the similarity of plant fossils 300 million years old that are found across the Atlantic Ocean.
- In the early 1900s, James Hall proposed the geosynclinal theory, which suggested that there are large troughs in the Earth, generally in oceanic areas, that receive sediment from the continents and then slowly subside. As they sink, they heat up and then start to fold in on themselves and create chains of mountains. The geosynclinal theory is a static model that involves vertical change, however; it is contrary to an idea of drifting continents, which implies lateral forces. Even so, the geosynclinal theory would remain firmly entrenched in the scientific literature until the 1970s.

- In 1910, a German meteorologist named Alfred Wegener wrote, “Doesn’t the east coast of South America fit exactly against the west coast of Africa, as if they had once been joined? This is an idea I’ll have to pursue.” In pursuing his idea, Wegener brought a great deal of evidence to the table.

Evidence in Land Masses, Lava, and Glaciers

- Consider the Appalachian Mountains, which pass up the east coast of North America, move into Newfoundland, and then seem to disappear into the Atlantic Ocean. But in Britain and into Scandinavia, we find mountains that are the same age, composed of very similar rocks, and have a comparable deformation—they have been crunched and folded in a similar way. This is called the Caledonian mountain chain, which existed about 400 million years ago.
- Throughout the world, it is not just mountains that match up; it is also stratigraphy, characteristic rocks, similar sediments, and comparable deformation histories. For example, lava in Africa almost exactly matches the chemistry and age of lava found in South America.
- Other evidence comes from glaciers. Wegener, in particular, was looking at a glaciation that occurred 280 to 270 million years ago. Glaciation leaves characteristic features behind in the landscape and in till—a lumpy sediment created when a glacier rumbles across a rock surface and chews it up. Glaciers also have scratch rocks embedded in their undersurfaces; as they move across a rock surface, they gouge characteristic lines or striations into them.
- When we look at glacial evidence and the direction of movement of those glaciers, we see that some glaciers are moving from the ocean and up onto the continents. Glaciers do not do that. If, however, we reconfigure the continent to form a southern polar continent that we call Gondwanaland, we have a much more reasonable climatic model to understand a large glaciation in the southern polar hemisphere.

Evidence in Coal, Corals, and Other Fossils

- More evidence of continental drift comes from coal, which is basically compressed plant material. Coal in the northern hemisphere generally comes from a period called the Carboniferous, 359 to 299 million years ago. That coal was deposited in a hot and swampy environment. Yet the majority of the coal that we extract today comes from temperate regions—that fact doesn’t fit with current continental configuration.
- Corals are also a good indicator of continental drift. Tropical corals are very specific to their environment: clear, shallow water at 77° to 86° Fahrenheit. Yet we find tropical coral fossils in the Arctic Circle. Again, this only makes sense if we can rearrange the continents so they match up with more reasonable climatic regimes.
- Other fossils help in understanding that the continents must have once been in different configurations. For example, we find the same fossil, *Lystrosaurus*, from around 250 million years ago, in India, South America, and Antarctica.
- A tropical fossil flora that we call *Glossopteris*, from 299 to 251 million years ago, is found in South America, Africa, India, Australia, and Antarctica. This is far too wide a distribution for a tropical flora. The distribution only makes sense when we reconfigure the continents to form an obvious climatic belt centered on the southern pole.

Wegener’s Hypothesis of Continental Drift

- Using his evidence, in 1915, Wegener published his hypothesis of continental drift in *The Origin of Continents and Oceans*. By the third edition of this publication, he proposed a supercontinent called Pangaea that existed more than 200 million years ago. (In Greek, *Pangaea* means “all lands.”)
- The scientific community rejected Wegener’s theory primarily because Wegener was questioning a basic, established scientific

paradigm. Wegener was the little boy in the crowd pointing out that the emperor was not wearing any clothes.

- Although Wegener had gathered enough evidence to suggest continental drift, the mechanism he proposed to explain why the continents moved was not acceptable. He suggested that centrifugal forces caused the continents to move. In addition, the gravity from the Sun and the Moon, he proposed, might also help shift the continents. Any physicist will tell you that there is not nearly enough energy in those forces to cause the moving of continents through oceanic rocks.

Hess's Theory of Seafloor Spreading

- The theory of continental drift was vindicated by events during World War II. Harry Hess, a geologist, was also the captain of the U.S.S. *Cape Johnson*, a transport ship outfitted with a new technology, sonar, to detect German submarines. Hess left his sonar on while he was crossing the Pacific Ocean and, in doing so, started to create profiles of the ocean floor. He discovered something quite amazing.
- The ocean floor in that area—in fact, all over the world—was not flat. It was covered with ridges, commonly with sunken volcanoes along the edges of continents. There was a deep oceanic trench. These findings were bizarre, because if the oceans had existed for billions of years, they should be full of sediment and completely flat.
- Hess suggested that in these long ridges that he found under the ocean floor, magma was rising up continually, generating new ocean crust. As that new ocean crust was formed, it would displace the older crust to either side. This older crust would eventually descend and be recycled back into the ocean trenches. Hess called this process “seafloor spreading” and, in 1962, published his ideas in an article entitled “History of Ocean Basins.”
- According to Hess, continents are the thickened parts of crustal plates, and the continents are carried on those plates. They move as oceanic crust spreads from the mid-oceanic ridge at its edge or

is subducted at another plate boundary. The movement is slow, but slow movement over time can cause significant change. Hess's work forms the basis of the theory of plate tectonics.

Plate Tectonics

- In plate tectonics, the majority of activity occurs at the plate boundaries. The divergent plate boundary is one where the ocean crust is continually being generated, oozing up. There is one area in the world where we can actually stand on a divergent plate boundary: Iceland. One part of Iceland is moving toward North America, and the other part is moving toward Europe.
- Convergent plates undergo an operation called subduction, where one plate is physically pushed below another into the Earth. There are three different processes involved here.



Each of the Aleutian Islands is essentially telling us that a plate is being pushed physically below it by the process of subduction.

- In ocean plate-to-ocean plate convergence, we find that an oceanic volcanic island arc develops above the descending plate due to the heating caused. We can see that in the Aleutian Islands, which is being developed as the Pacific plate is pushed below it.
- In ocean plate-to-continent plate convergence, one of the first things that happens looks like a train wreck. Because continental rocks are not as dense as oceanic rocks, they cannot physically be subducted. The edge of the continent gets ripped up. These ocean plate-to-continent plate collisions generate volcanic activity, such as the activity we see in the Pacific Northwest.
- When two continental plates meet, in continent plate-to-continent plate convergence, there is only one way for them to go: up. We see that most spectacularly in the Himalayas, which represent an ongoing collision between India and Asia.
- At a transform plate boundary, the plates just slide past one another. In California around San Andreas, the North American plate and the Pacific plate are moving past each other but not smoothly. The plates can stick, build up pressure, and then suddenly give, generating earthquakes.

The Concept of Deep Time

- Tectonic plates move very slowly. The Atlantic plate, for example, is spreading and opening at about the same rate that fingernails grow. This is why the concept of deep time is very important to add to our understanding. Over the vast extent of deep time, the Earth's processes can cause mountains to rise or whole ocean basins to be opened up and removed.
- With our understanding of Earth as an ancient body whose surface is shifting because of plate tectonics, we are ready to open up a window into Earth's past. We will interpret the ancient biospheres in the light of all that we have covered so far.

Suggested Reading

Kious and Tilling, *This Dynamic Earth*.

McCoy, *Ending in Ice*.

Questions to Consider

1. Given that it is very difficult to actually see Earth's plates moving, how reasonable do you think the opposition was to Wegener's hypothesis of continental drift?
2. Is it possible that any of the widely held scientific views of today could be turned around in the same way that plate tectonics completely altered the way we understand how the Earth worked in the late 1960s and early 1970s?

Earliest Origins—Formation of the Planet

Lecture 6

This lecture explores the earliest origins of our planet and how the Earth and the entire solar system were formed. We'll look at how the Earth progressed from an abiotic, lifeless orb to our current layered and differentiated planet, and we'll investigate how the formation of the solar system influenced the evolution and development of life on Earth.

How the Solar System Formed

- The Earth is a system that itself is part of a larger one, the solar system. If we are going to understand the Earth as the cradle of the biosphere of life, we need to know how the Earth formed in the context of the solar system.
- According to the solar nebular disk model, the solar system originally began as a massive cloud of interstellar hydrogen and dust. That cloud then started to collapse in on itself. As it contracted, it started to spiral down into a central mass. We think that about 90 percent of the mass of that cloud would have been the elements in the center.
- About 100,000 years after that initial collapse, a flattened, rotating disk called the accretion disk formed, which was about 200 astronomical units across. (An astronomical



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We imagine that the Eagle Nebula resembles the original nebula that formed our solar system; the pillars are concentrations of dust and gas, probably where young stars are forming.

unit is the distance from the Earth to the Sun, about 93 million miles.) Grains of dust in that accretion disk started to knock into each other and clump together, and their gravity started to attract other lumps of material, the clumps growing larger over time.

- As time progressed, temperature and pressure increased as more material was added to the center. This was the embryonic period of the Sun, when it was still a protosun. Astronomers call this the T Tauri protosun phase of solar system formation.
- After about 50 million years, following the initial collapse of the nebula that would form our solar system, there was a remarkable event—in fact, a holy grail of physics: Positively charged hydrogen nuclei started to fuse together.
 - Because hydrogen nuclei have positive charges, they really want to repel; they do not want to combine.
 - But the pressure and temperature were so high in the central mass of that cloud that the repulsion was overcome and the hydrogen atoms were fused together, forming helium and a tremendous amount of energy. Then, the Sun switched on.
- Close to the Sun, the inner planets continued to go through massive collisions. This is called the merger phase. After about a billion years, the planets reached their current size. In fact, it is thought that the Earth and Venus probably formed by the collision of embryo planets. This would have been a very violent and busy time in the early solar system.

How the Earth Formed

- The Earth is a layered and differentiated planet. Looking at a cross-section of the Earth, we see that it has distinct layers with different densities. Structurally, it has a light crust surrounding increasingly denser material, with the densest material being right in the center.
- A hypothesis that attempts to account for this is called the cool accretion hypothesis, which suggests that the Earth originally

accreted cold. In the accretion disk, we had lumps of dust and rock clumping together, and then clumps of clumps clumping together—eventually forming what can be described as a large rock pile in space.

- But in order to differentiate this rock pile, it must be heated up. The theory is that it was heated up by two processes. First, as the planet got larger, collisions between rocks got more catastrophic and released more energy; the energy of those impacts heated the planet up. In addition, a great deal of material was being concentrated, some of which was radioactive. When radioactive material decays, it gives off energy. That also helped the rock pile to melt.
- As the rock pile heated up, the heavy material under gravity, mostly iron and nickel, sank to the center of the Earth, forming the core. The much lighter materials, such as carbon, silicon, and aluminum, remained concentrated on the surface.
- The result was a layered Earth with abundant carbon-based materials on the surface and a metallic core—and a planet that, possibly because of varying densities, would initiate plate tectonic processes. Each of these factors is vital in our understanding of the evolution of our planet and especially of its biosphere.

The Hadean Period

- These early times, 4.54 to 3.8 billion years ago, are called the Hadean period. We have very little record of it, however. In the past, even without atmospheric oxygen, our planet had a very erodible surface. Plate tectonics also recycled parts of the crust, and impacts affected the record of Earth's early history.
- One remnant of the Hadean period is the oldest rock found to date. It is called gneiss, which means it's a fairly high grade of metamorphic rock. Metamorphic rocks are those that have been heated and pressurized. This particular rock exhibits bands of different minerals. Analysis of it suggests that it was originally a granite from about 4 billion years ago.

Significance of the Moon

- The Moon was vital in the development of our biosphere. It had and continues to have a much more profound effect on the Earth than simply the tides—although those are significant. Three important features of the Moon were crucial to the formation of the biosphere on our planet.
- First of all, consider the Earth in space. The Earth's axis is not vertical; it's tilted to the plane of ecliptic at about 23.5 degrees. This tilt, or obliquity, changed slowly over about 41,000 years, and it appears that the variation in the degree of tilt is possibly linked to climatological cycles. It might explain, in some way, the periodicity and frequency of glacial episodes, for example.
 - The Moon has had a stabilizing effect on that wobble, however. It is thought that if it were not for the Moon's gravity holding the Earth in place, that wobble would have been more severe. In that case, the Earth would have experienced many more severe and dramatic climatic shifts.
 - Because of the Moon, we have a more stable climate, and if we have more stable conditions on our planet, that means we have the potential to develop a more stable biosphere with greater complexity.
- Second, the Moon is unusually large compared to the planet it orbits—Earth. That has consequences for impacts from outer space on the surface of Earth. We can think of the Moon as being a bit like a large catcher's mitt. Although the Earth has received many impacts, the Moon had probably taken some of those hits. If the Earth is getting hit less frequently than it would have been otherwise, the Moon has allowed for the development of a more stable biosphere and more complex life forms.
- The third important feature of the Moon is the impact of tides. To help explain this, we'll discuss the most current hypothesis about how the Moon was formed.

Formation of the Moon

- It is now thought that the Moon was formed by the impact of a Mars-sized planet around 30 to 50 million years after the origin of the solar system. The material from that impact—parts of the Earth itself and the impactor—was ejected into Earth's orbit. This material orbited our planet Earth and eventually coalesced over time to form the Moon that we can see today. This theory also explains why our planet has quite a tilt: It has been knocked askew by a large collision. It may also explain why the Earth has a relatively fast spin.
- Interestingly, this fast spin has been confirmed by something rather unusual: coral fossils. Corals are creatures that secrete a calcium carbonate, known as calcite, in their skeletons. They lay down a layer of calcite every day. These rings tend to be grouped into months, and through analysis of these rings, we can get an idea of the length of a year. Scientists have analyzed certain late Devonian corals, from around 360 million years ago, and concluded that, during the Devonian, a year had 400 days. It would appear that the Earth has been slowing down, about 2 seconds every 100,000 years.
- If we were to look up at night during the early Precambrian era—the time in Earth's history not too long after the Moon had formed—we would find that the Moon absolutely dominated the sky. It was about 200,000 miles closer than it is today. It would have been an absolutely spectacular feature in the night sky.
- However, it would also have been a fairly precarious time. One of the features of the Moon is that it is responsible for the Earth's tides. In those times, we had a Moon that was much closer; therefore, the gravitational forces would be that much more severe. In fact, the tides were not really very much like tides; they were more like mega-tsunamis. Those tsunamis would have scoured the early continent, washing minerals and nutrients into the oceans and thoroughly mixing the oceans up. In this way, it's thought that the Moon was the spoon that mixed the brew of life from which the biosphere developed.

- Before we move on to describe the formation of the Earth's biosphere, we'll consider where the other major systems come from. We'll explore the origin of the lithosphere (all the rock), the atmosphere (the gassy envelope that surrounds our planet), and the hydrosphere (all the water)—because it is in these spheres of the Earth's system that the biosphere would evolve.

Suggested Reading

Faure and Mensing, *Introduction to Planetary Science*.

Varricchio, *Inconstant Moon*.

Questions to Consider

1. It would appear that solar systems and planets are common in our galaxy. With this in mind, is it likely that Earth-Moon systems like our own are very common?
2. The Earth is regarded as being about 4.54 billion years old, but what do you count as day 1? When the first seeds of the planet came together or when the Earth reached its current mass?

Origins of Land, Ocean, and Air

Lecture 7

This lecture explores three major Earth systems: the lithosphere, atmosphere, and hydrosphere. We'll also answer three important questions about the events following the formation of the solar system, the Earth, and the Moon: Where did all the land come from, what is the nature of the early Earth's atmosphere, and what created the oceans? These are critical questions because it is in this earliest iteration of Earth systems that life would evolve.

The Earth's Crust

- Initially, the Earth was a huge magma sea hanging in space. As that magma cooled, a skin formed on its surface. Today, that skin, or the crust, represents less than 1 percent of the Earth's total volume, but it holds much of the geological and paleontological information that we are studying here. The Earth's crust is composed of two types: oceanic crust and continental crust.
- Oceanic crust is generated in oceanic ridge systems. Magma is injected in these ridges, moving the old material to the side, and eventually, that material is removed and subducted at the plate margins. Ocean crust is about 4.3 to 6.2 miles thick, and it has a very specific structure.
- Fragments of ocean crust exposed above sea level are called ophiolites. If we walked along an ophiolite, at the very bottom, we would see some of the material below the crust. It is very dense material, like mantle rocks. Above that is a material called gabbro, a dark rock that represents a magma chamber at a spreading ridge. Above that magma chamber, feeder pipes take the magma to the surface of the ocean, where it erupts as lava called pillow lava. Above the pillow lava is usually a thin cover of ocean sediments.

- Overall, the crystal composition of the ocean crust is basalt. It is composed of iron-rich and magnesium-rich minerals, which explains why these rocks are fairly dense and dark in color. We describe the oceanic crust chemical composition as mafic. *MA* stands for the magnesium minerals we find in the rocks; *FIC* stands for the iron (*ferrum* is Latin for “iron”).
- Continental crust is about 15.5 to 43.4 miles thick. Overall, the composition is similar to granite, composed of lighter-colored elements, such as aluminum and silicon. Silicate minerals are far less dense than gabbro. The term we give to this rock is felsic; *FEL* stands for feldspar, and *SIC* refers to silica.
- Today, the Earth’s crust consists of a thin oceanic crust and a thick but lighter continental crust riding above it because of the recycling of the ocean crust. No ocean crust is older than 180 million years old. Because continental crust is lighter, it’s less dense, and it very rarely gets subducted into the denser mantle below the crust. As a result, the continental material tends to sit around over many millennia. Therefore, the oldest rocks will be found on the continents.

How the Continents Formed

- Earth’s first crust was probably all basaltic, like oceanic crust. Continental crust was produced from the thin skin of basalt by recycling that skin at subduction zones. If two oceanic plates come together, the older plate subducts because it is cooler and denser. As the subducting plate descends, it heats up, and water gets driven up the plate. The release of that water into the mantle above the descending slab causes melting in the mantle.
- Mantle rock—for example, peridotite—is composed of different minerals, each of which has a different melting point. When the mantle rock melts, only some of those minerals melt, however—this is called a partial melt. Magma will be generated with a different composition than the mantle rocks that are being partially melted.

The magma that is produced is not going to be like peridotite or mantle rocks.

- The mantle rock produced is called ultramafic. These rocks are very high in iron minerals and very dense. The magma produced by partially melting an ultramafic rock is a mafic rock. It will be less dense than the surrounding rocks from which it is produced, and it will be extremely hot, so it rises. The magma rises and gets erupted through the overriding plate to form small basaltic islands.
- These islands are the first seeds of continents. Imagine an Earth with lots of little volcanic islands dotted all over it, but with no large continental land masses. Over time, those islands moved around on the plates and collided and amalgamated, making larger and larger land areas. These are mafic basaltic islands.
- As the continents grew, they became thicker, but where does the felsic material come from? Scientists believe that felsic material was produced through subduction below those growing volcanic islands. As the magma generated by this subduction rose into these islands, a process called magmatic differentiation produced magmas of lighter composition. Once those felsic magmas cooled to form granites and similar rocks, they were far too light to be subducted. They simply accumulated over time.

Ur: The First Continent

- We have evidence of Earth's early crust from rocks that were derived from earlier progenitors—zircon crystals from Australia that were eroded from a very old rock. These crystals were incorporated in a sedimentary rock called a conglomerate. When these zircons were radiometrically dated, they were found to be 4.4 billion years old. That means there must have been some sort of solid surface back then in Earth's history.
- The first large continental land mass, called Ur, was formed about 3 billion years ago. We can still find fragments of Ur preserved in present-day Australia, Antarctica, India, and Madagascar.

- Seed continents continued to grow by continental collision and accretion over all of geological time. In fact, the process is still going on today. Many continents form fragments and recombine over time.
- The supercontinent of Rodinia formed about 1.2 billion years ago and fragmented just 650 million years ago. It fragmented during the lower Paleozoic era and then recombined about 200 million years ago to form the supercontinent of Pangaea.



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The Earth's Protective Shield

- Earth grew out of a nebula of gases: hydrogen and helium. After fusion had initiated in the Sun, there was a release of solar radiation, generating a strong solar wind. We can see some of those strong solar winds, called solar flares, today. When they erupt, they release energy—the equivalent of billions of hydrogen bombs in just one event.
- How does the Earth stay safe from these solar flares? We can get a hint from a spectacular feature in the night sky: the aurora borealis in the northern hemisphere, or the aurora australis in the southern hemisphere. These auroras are formed by charged energy particles from the solar wind interacting with the Earth's magnetic field. The phenomenon is an indication that the Earth's protective shield is in operation. We call this protective shield the magnetosphere. It has been protecting the biosphere from solar storms for billions of years.

The supercontinent Pangaea formed about 200 million years ago from the fragments of the earlier supercontinent, Rodinia.

- The Earth has a solid inner core, but around it is a layer of rotating liquid metal. Because that area is rotating, it sets up a dynamo effect that generates Earth's protective magnetic field.

How the Atmosphere Formed

- Before the magnetosphere was in place, the first atmosphere of hydrogen and helium disappeared. Where did that second atmosphere come from? To answer that, we turn to volcanoes. Volcanoes are a feature of the planet that allows for planetary degassing.
- Our planet is continually trying to lose heat. The heat-loss process releases a great deal of gases. We think that the initial Earth atmosphere that developed after the formation of the magnetosphere would have been fairly similar to current volcanic emissions: lots of water, carbon dioxide, hydrogen, nitrogen, sulfur-based gases, and chlorine. The proportions of the gases may have varied, but there was probably a great deal of water and carbon dioxide in those gases. Today, the atmosphere is 78 percent nitrogen and 21 percent oxygen, with a variable amount of water vapor.

Water from Space

- Initially, the Earth's water was most likely also produced by volcanoes. That water vapor produced by volcanic emissions was held in the atmosphere for some time because the Earth was initially too hot to allow for condensation—to allow rainfall to initiate. However, there came a time when the Earth reached that critical temperature, when the first raindrops started to fall to the surface of the planet. And it probably rained for centuries.
- However, we don't believe volcanic emissions account for all the water that we find on the surface of our planet today. There must be another source. We think that other source is extraterrestrial—from comets.
- Comets range in size from a few hundreds of meters to tens of kilometers. They are generally composed of various ices and debris—they are like dirty snowballs in composition. In 2005,

NASA studied an impact of a comet that created a crater about 330 feet across. Within the large plume of material created by the impact was about 11 million pounds of water.

- The theory is the early solar system had a great deal of water in it, and many more comets impacted the Earth. Some of those comets delivered water.

How the Hydrosphere Formed

- Initially, Earth's oceans would have been freshwater, but the erosion of rocks and the introduction of minerals at volcanic vents eventually turned the oceans salty.
- When do we have evidence of the first liquid water? The oldest sedimentary rocks that were deposited in water and the oldest features on some igneous rocks deposited or erupted in water come from Greenland and are about 3.8 billion years old.
- Earlier evidence is in the zircon crystals from Australia. Some of the oxygen isotopes found in those crystals suggest that the parent rock that formed them developed in an environment that had liquid water. If this is true, it pushes back liquid water as a reality on the surface of our planet to about 4.4 billion years ago. That means we have a potential cradle of evolution far back in geological time. With water, life processes can potentially start moving along. The stage is now set.

Suggested Reading

Lindsey, "Ancient Crystals Suggest Earlier Ocean."

Wicander and Monroe, *Historical Geology*.

Questions to Consider

1. Do the principles of Hutton, that the present is the key to the past, break down the further we explore the deep history of our planet?

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2. If comets account for a large proportion of Earth's water, is it possible that other planets and moons in the solar system may also contain water resources? What implications does this have for human expansion into the solar system?

The Early Chemical Evolution of Life

Lecture 8

The origin of life has intrigued humans ever since the dawn of consciousness. In this lecture, we will look at a number of possible scenarios for the origin of life on our planet. Did life emerge, as Charles Darwin supposed, from some warm little pool, or should we look to the deep ocean environment for life's origins? Did life—or at least the building blocks of life—have a more exotic, perhaps extraterrestrial, origin? What were the first stirrings of life like?

Life as Part of the Earth System

- In 1871, Charles Darwin wrote a letter to botanist Joseph Hooker regarding the origin of life; he said, “We could conceive in some warm little pond, with all sorts of ammonia and phosphoric acids, light, heat, electricity, present.” Darwin thought that this was the



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Charles Darwin believed that life originated in some sort of volcanic pool, and some scientists today are still in favor of this idea.

brew from which proteins could form, and from proteins, we could move to the progenitor of all life.

- What is important here is not Darwin's methodology for the origin of life but, rather, that he suggested that life emerged inorganically—life being an emergent property of the evolution of a developing Earth system.
- Before the 19th century, there were very different views regarding the origins of life. In addition to biblical accounts, there was the theory of spontaneous generation. For example, if someone left putrid matter on the floor, it was thought that fleas spontaneously generated from that.
- After Darwin, spontaneous generation was replaced by evolution through natural selection. However, there is one part of life's story where spontaneous generation still plays a part—right at the beginning. But we no longer call it spontaneous generation; we call it abiogenesis—effectively, life from lifelessness.
- Abiogenesis was supported by Alexander Oparin, a Russian biochemist. In studying the atmospheres of the Jovian planets, Oparin noted that while many of their gases were carbon-based gases, such as methane, there was water vapor, ammonia, and a great deal of hydrogen present. He surmised that these gaseous giant atmospheres could be analogous to Earth's primitive atmosphere. Oparin also theorized that inorganic systems were arranged in hierarchies of increasing complexity. He suggested that life is just one extra level of chemical complexity of the system.

The Miller–Urey Experiment

- The idea that we could move toward some sort of life was tested in 1952 by Stanley Miller and Harold Urey at the University of Chicago. They designed an experiment—the now-famous Miller–Urey experiment—that recreated the conditions on the early Earth. They took the gas giant atmosphere as an analog for the early Earth atmosphere, using water, ammonia, methane, and hydrogen.

- Miller and Urey created a closed system, using glass tubing.
 - The bottom of the experimental assembly was full of liquid water, representing the early oceans. That water was heated, and as it heated, it evaporated and rose up into the vessels that simulated the atmosphere.
 - Eventually, that atmosphere passed into an object at the top, where two prongs delivered electricity and created a spark. This simulated lightning, an energy source in the early Earth atmosphere.
 - The atmosphere then moved around the system, cooled, and ultimately condensed and was returned to the ocean, where it was again heated and recycled through the system again and again.
- Miller and Urey left the experiment going for a week and then came back. What they found was that system no longer looked like an inorganic system; it was full of dirty, black muck. When they analyzed it, they found that it contained something extraordinary: organic compounds, including amino acids.
- Amino acids are the building blocks of proteins. Proteins are important food sources for some creatures, but they also form important parts of DNA, DNA-related components, and cell membranes. It would appear that the early Earth atmosphere was conducive to forming life molecules.
- Interestingly, there is supporting evidence for this hypothesis that comes from the studies of what we call old genes. These are genes that are common to most life forms on the planet—in other words, they share a common ancestor. These old genes are rich in the type of amino acids produced by the Miller–Urey experiment.

Life from the Ocean

- Another possible scenario for the origin of life lies in the deep ocean. Along ocean ridges, where there are plate margins, new oceanic

crust is created. Pillow lavas are generated in this environment, and the rock close to the ocean ridge remains hot for a long time. Ocean water seeps into this crust through cracks, and as it descends into these hot crustal areas, it heats up.

- As the ocean water heats up, it starts to circulate through the crust, dissolving minerals as it goes. Then, eventually, it is returned to the surface in geyser-like structures called black smokers. Its chemical composition contains metals, sulfides, and very hot water. When this brew comes into contact with ocean water that is charged in carbon dioxide, it catalyzes reactions that, again, form many biologically useful organic molecules.

Life from Outer Space

- Does life on Earth have extraterrestrial origins? In 1969, an astounding discovery was made. A meteorite was found in Murchison in Victoria, Australia, that is part of a class of meteorite called a carbonaceous chondrite; as the name suggests, it is very rich in carbon. But this carbon is not just the usual carbon or graphite. It contains amino acids—the building blocks of proteins. It also contains alcohols, phosphonic acids, and nucleobases, some of the basic components of molecules like DNA.
- Earth was bombarded with comets and meteorites early on in its history. It is likely that organics were frequently deposited from space. But it is also quite likely that we were generating organics on the Earth, as well—from the atmosphere and in the ocean. Creating those live chemicals is no problem; however, they are still not life.

What Is Life?

- We can think of life as having four essential components.
 - First, life must demonstrate some sort of organization or structure.
 - Second, it must be separated from its external environment—most likely through some kind of membrane.

- Third, it must generate energy; it has to be able to metabolize in some way.
- Fourth and probably most important, it needs to be able to replicate itself. It needs to be able to preserve its kind and pass copies of itself into the future.
- The Miller–Urey experiment, however long it was left switched on, did not produce life. It was obviously missing an important factor—one that we really can't account for experimentally: deep geological time.

The Catalyst for Life

- We know that we can create simple important life molecules—sugars, amino acids, and so on—but that is not life. We need to get these organic molecules together. We need to polymerize them into more complex organic molecules, strings of molecules.
- One way to do this is to catalyze the reaction—that is, use something that will independently help these molecules get together and generate longer-chain molecules. A common way to catalyze is to use polyphosphates. In fact, one of the most common catalyzing agents, or energy generators, is adenosine triphosphate (ATP).
- Another source of catalyzation is clay. Clay is a fine-grain sedimentary particle. When it is found in the oceans, however, it takes on positive and negative electrical charges. Those charges attract organic molecules to its surface, which can then align along the surface of the clay.
- Radioactivity is another possible catalyst. It is thought that the early Earth had more phosphoric radioactive minerals than today. These minerals would tend to be concentrated on beaches. It's possible that some of these radioactive minerals back in the early Earth times were concentrated by ocean waves, and the phosphorus and radioactive activity helped catalyze reactions.

Self-Replicating Molecules

- For life to prevail, ordinary long-chain molecules are not enough; we need something special—a self-replicating molecule. We need something that will pass copies of itself down through time. Of course, the most prominent self-replicating molecule is DNA. But we have a problem: DNA needs a hand in replicating itself.
- Fortunately, there is a way out of this paradox that is related to DNA called ribonucleic acid (RNA). There are many different forms of RNA.
 - Messenger RNA (mRNA) goes into the nucleus of cells where recombinant DNA is stored and makes copies of the coded messages on the DNA. It then takes copies of those messages out into the cell to help code for proteins in the cell's cytoplasm.
 - Transfer RNA (tRNA) brings specific amino acids to these assembly points to help build proteins.
 - Ribosomal RNA (rRNA) is the one of greatest interest to us because this RNA helps catalyze the formation of proteins. Possibly even more significant, rRNA can also self-replicate.
- In 1996, Walter Gilbert of Harvard University proposed the existence of an RNA world, an early planet dominated by self-replicating naked genes of RNA before the emergence of life that was based on DNA. In the RNA world, RNA molecules competed for component molecules, for the nucleotides that made themselves up.
- These forms that could catalyze their own development would have a selective advantage. In this scenario, evolution by natural selection had been initiated, potentially, even before life really got going at all. Evolution by natural selection preceded almost the evolution of life itself.
- The biosphere does not exist in isolation. The evolution of life affects every Earth system—the hydrosphere, lithosphere, and

atmosphere. Our next lecture will look at some of the first evidence that we have on our planet for the emergence of life.

Suggested Reading

Knoll, *Life on a Young Planet*.

Ricardo and Szostak, “The Origin of Life on Earth.”

Schopf, ed., *Life's Origin*.

Wicander and Monroe, *Historical Geology*.

Questions to Consider

1. Is it possible for scientific hypotheses of the origin of life to coexist with the creation accounts of the world’s religions?
2. Given that organic material appears to be very common in the galaxy, should we be surprised if we don’t find life in our solar system?

Hints of the First Life Forms

Lecture 9

This lecture examines the evidence of early life on our planet. We will explore the question of whether life began on Earth or whether it arrived from another place entirely. Further, we'll look at Earth's oldest fossils and consider how life survived in what was at that time a very crowded solar system. We'll speculate about the possibility that life evolved more than once, or whether it simply hid away when the planet was bombarded from outer space.

Life from Mars?

- In December 1984, a meteorite was found by a U.S. team in the Allan Hills area of Antarctica. Scientists look for such specimens in Antarctica because dark meteorites show up against the white background of the snowy landscape; also, these meteorites tend to get locked in ice, which removes them from the highly oxidizing atmosphere.
- The meteorite recovered was one of a series that, through gas analysis and other techniques, was determined to have come from Mars. The Allan Hills meteorite, commonly called ALH 84001, is probably one of the most legendary meteorites in the world. In 1996, it hit the headlines and became an instant international superstar. The reason: It was claimed that fossils were found within this meteorite—fossils from Mars.
- Scientists believe this Martian rock was originally a magma that crystallized to form an igneous rock around about 4.1 billion years ago. Around 4 to 3.9 billion years ago, it was fractured in a meteorite impact and lay exposed on the surface of the planet. At that particular time, Mars was warmer and wetter and probably had areas of open water. The speculation is that the rock later became encrusted or invaded with microbes, and eventually, those microbes became fossilized.

Evidence of Life in Meteorites

- Is this meteorite truly a fossil? Some of the structures found in the rock are 20 to 30 nanometers in length, smaller than the smallest bacteria discovered on our planet. Some scientists have questioned if it is even possible for biochemistry to work on this small scale. Also, certain inorganic processes, such as mineral deposits, can replicate fossils: Pseudofossils can mimic true fossils in some way.
- Other chemical evidence, however, suggests that these structures are actually life forms—or at least previous life forms. One of those pieces of evidence in the meteorite is the presence of polycyclic aromatic hydrocarbons (PAHs), common decay products of bacteria.
- The meteorite also contains rosette-like structures that have cores of manganese surrounded by rings of iron carbonate and iron sulfides. These bear a strong resemblance to mineral features that are produced by terrestrial bacteria today. What's more, the meteorite contains magnetite crystals; magnetite is also found in certain bacteria, such as magnetotactic bacteria.
- While we have demonstrated what seems to be strong evidence of fossil life on Mars brought to Earth in a meteorite, there is a problem. All the evidence described here can be explained by some sort of inorganic process. If we assume that these are real fossils, however, we get an interesting alternative to the evolution of life.

Panspermia

- Because Mars is much smaller than Earth, it would have cooled much faster and developed liquid oceans before Earth did. If that's the case, the question is whether it is possible that life evolved on Mars before it did on Earth. Imagine the developing Martian bacterial biosphere. Mars at this time was still receiving many impacts from space, and because Mars has less gravity than Earth, it is easier to launch rocks off its surface—and any microbes on those rocks.

- If Mars seeded our planet, however, how could microbes survive the vacuum of space? In fact, bacteria have been found to survive three years of exposure to vacuum, radiation, and extremes of cold and heat with no available sources of nutrition and water.
- The idea that life was seeded from elsewhere is called panspermia; it is regarded by many as a fringe science. But given our understanding of the hardiness of microbes and of the possibility of microbial life on Mars at one time, perhaps it is not quite as close to science fiction as previously thought.

Evidence of Photosynthesis

- To help determine where and when life began, let's look at the oldest fossils that we can be sure are from Earth. The oldest structures that are considered fossils come from the Apex Chert formation in Australia and date to about 3.5 billion years ago.
- Chert is a fine-grain silica deposit that closely resembles certain bacteria called cyanobacteria. Their more common name is pond scum. Pond scum might not seem exciting, but actually, these are remarkable creatures that represent the development in the biosphere of an incredibly complex process: photosynthesis.
- Photosynthesis is a process whereby sunlight is used to convert carbon dioxide into organic compounds and oxygen. If the oldest fossils on our planet are photosynthetic fossils or provide evidence of photosynthesis, then life must have a vastly long history.

Evidence of Water and Carbon

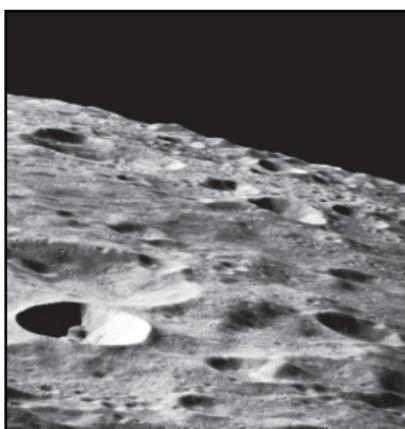
- In the Isua formation in Greenland, there are potential hints of life that date back to 3.8 to 3.7 billion years ago. Isua provides the first direct evidence that we had open water on the surface of the planet. The Isua complex has the oldest structures that we can positively identify as being formed in water: pillow lavas.
- Pillow lavas, basaltic in composition, are lavas that erupted underneath water—very commonly underneath the ocean. The

pillow lavas found in Isua are an important indicator of the presence of water.

- In Isua are also found sedimentary rocks with dark bands that contain particles of carbon. It has been speculated that these particles of carbons were produced by microorganisms. There are three isotopes of carbon: carbon-14, the unstable variety that decays and that we use to radiometrically date relatively recent objects, and the two stable isotopes, carbon-12 and carbon-13.
- Photosynthesizing life has a preference for organic carbon dioxide, which is carbon-12. Organisms tend to be enriched in carbon-12, and a high concentration of carbon-12 could indicate that photosynthesis was occurring. The carbon-12 signature was found within those carbon blobs at Isua. If it indeed indicates the presence of photosynthetic life, it means that life existed more than 3.7 billion years ago.

The Late Heavy Bombardment Period

- Considering the active and violent beginning of the solar system, an important question to ask is how life survived in what was, at least initially, a very crowded solar system. Mercury, Mars, and our Moon show evidence of intense battering 4.1 to 3.8 billion years ago during a time termed the Late Heavy Bombardment (LHB) period.



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The surface of the Moon records the intense battering of the Late Heavy Bombardment period; most likely, Earth also suffered severe and extremely large impact events.

LHB period, like much of the evidence of the very early history of our planet, has been removed by plate tectonics and erosion, but the other planets certainly record it. There is no reason to expect that Earth would not also have suffered severe and extremely large impact events.

- These catastrophic impacts would have formed craters thousands of miles in diameter, spewing rock vapor high up into the atmosphere. The impacts would have superheated the atmosphere to such an extent that the oceans would have boiled and evaporated away into the atmosphere. The Earth's crust may have started to melt. After massive impact events in the LHB period, the surface of our planet would have been, in effect, sterilized.

Archaea: The Ultimate Survivors

- Here is the paradox: If life was already becoming complex 3.8 billion years ago and if it existed before the LHB period, how did life survive? Could life have evolved more than once? Genetic evidence suggests that the origin of life is before the LHB period, and there is a single train of life to the present. The question is: Where did life go to hide?
- The answer may be found in hot, hydrothermal vent systems found around mid-ocean ridges. The water in these systems is full of toxic heavy metals. It is close to boiling and is subject to tremendous pressures. But we also find life there.
- Bacteria can survive in those conditions—but only a particular kind of bacteria. Although we call these creatures bacteria, they are, in fact, simpler than bacteria: the archaea. The species *Archaeoglobus fulgidus* is found in hot sediments near submarine hydrothermal vent systems. It exists in temperatures around 181° Fahrenheit.
- Archaea are probably some of the most primitive representations of creatures on our planet. They are found in many environments with extremes of temperature and pH. That's where they get the name "extremophile." Some live in salty brines and some live at very

great depth. Archaea have been found 2 miles under the ground, where the water inside the rock is about 140° Fahrenheit. There's no oxygen or light, but life is pervasive at these great depths in the planet.

- This is the answer to the LHB paradox: Imagine the heat pulse from the impacts on the Earth. The heat pulse might have melted the very surface of the rocks but would have never reached deep enough to sterilize all those creatures, all those archaea, potentially living within the crust. They could survive there until temperatures on the surface of the planet cooled, the oceans condensed, and water rained on the surface. Then, life could migrate back to the surface of the planet and start again. Life had a lifeboat.
- Perhaps life's earliest ancestor was not from Darwin's warm little pool; perhaps it is the archaea living in near-boiling water deep within the crust of our planet.
- The next lecture will investigate the possibility that life almost destroyed the biosphere, ended its story, and encased our planet in a tomb of ice.

Suggested Reading

Gould, ed., *The Book of Life*.

Knoll, *Life on a Young Planet*.

Lane, *Life Ascending*.

Questions to Consider

1. Do you find the possibility that we might be Martians disturbing?
2. If life is so robust as to survive being exposed to the conditions on the surface of the Moon, is it possible that with our own exploration of space, we have become agents of panspermia?

How Life Transformed the Early Earth

Lecture 10

If we traveled back in time to the Earth following the LHB period, we would find a warm planet, not a frozen one, rich in methanogenic archaea. The Moon, which was closer to our planet in those times, would have appeared spectacularly large in the sky—a sky not blue but pink, owing to high levels of methane in the atmosphere. This lecture discusses the early beginnings of our modern atmosphere; why the planet was warm, not frozen; and how life's story almost ended entirely encased in ice.

Methane Atmosphere

- The Earth and the solar system are continually evolving, changing over time. Initially, our Sun was only 70 percent as luminous as it is today. Because the Sun was not as powerful, the Earth did not receive as much heat. The oceans should have been frozen.
- Yet we have found evidence of liquid water and life where there should have been ice and no life at all. This is known as the faint young Sun paradox. In fact, we think that life may actually hold the answer to this paradox.
- The simple bacteria called archaea are the answer. Many archaea are methanogens, which means that via various metabolic processes, they produce methane as a waste gas. This is not unlike the process by which cyanobacteria produce oxygen as a waste product of photosynthesis.
- Methanogens are some of the most ancient life forms on Earth. Methane was probably a major constituent of the early atmosphere following the evolution of the biosphere. There were lots of methanogenic bacteria around—all metabolizing and releasing methane into the Earth's system.
- Methane is also a greenhouse gas—about 20 times more effective than carbon dioxide. It would appear that the first life or some of

the earliest life on our planet actually emitted the gas that helped keep the planet warm, warmer than it should have been.

Accumulation of Oxygen

- Today, we have an atmosphere consisting of about 21 percent oxygen, but in Earth's early history, there was hardly a trace of oxygen in the atmosphere. At that time, this was advantageous, because high levels of oxygen would have been detrimental to the development of early organic molecules. Oxygen is an aggressive molecule that tends to break down organic compounds.
- We see the beginnings of our modern atmosphere when oxygen accumulated in the atmosphere via photosynthesis. Although the exact time of the evolution of photosynthesis is still very much debated, it is generally agreed that cyanobacteria had probably evolved by 3 billion years ago. The consequence of that evolution was an increase in levels of atmospheric oxygen.
- Certain structures called stromatolites are produced in sediments, layered with cyanobacteria. These stromatolites are evidence that



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Stromatolites in Shark Bay, Australia—sedimentary structures produced by the presence of life—give us a picture of the landscape of the early Earth.

cyanobacteria were spread across the planet. As stromatolites and cyanobacteria spread, oxygen levels rose. About 2.5 billion years ago, we start to see the impact of that rise in oxygen. One of the most dramatic pieces of evidence we have of the sudden emergence of oxygen comes from a rock called a banded iron formation.

The Great Oxygenation Event

- Banded iron formations consist of iron minerals—in particular, two iron oxides, the minerals hematite and magnetite. Before oxygen was present in the Earth’s system, iron existed in the oceans in a reduced ferrous state referred to as Fe^{2+} . Iron was eroded from rocks on the continent and transported in solution into the oceans. As oxygen was added to the Earth’s system, it combined with that iron in solution in the oceans and converted Fe^{2+} into ferric iron, Fe^{3+} , creating banded iron formations.
- These bands of iron are extensive and represent vast areas of deposition of iron-based minerals. The first evidence of banded iron formations comes from about 3.5 billion years ago. The formations peaked in abundance at around about 2.5 billion years ago but dwindled and became rare after about 1.8 billion years ago.
- The emergence of oxygen represented by the banded iron formations is called the Great Oxygenation Event; it would have profound consequences for the future evolution of the Earth’s system. Eventually, more oxygen was produced than could be used up by the iron, and that oxygen started to escape from the ocean and travel into the atmosphere.

Oxygen: The Toxic Gas

- Oxygen was highly toxic to the early biosphere. In fact, very early life had evolved and developed in an oxygen-free world, which explains why many of Earth’s most primitive organisms today are found in extreme environments with little oxygen. The ancient organisms retreated from this new toxic gas; the Great Oxygenation Event could have caused Earth’s first mass extinction at the microbial level.

- The increasing presence of oxygen also had consequences for our greenhouse blanket of methane. When oxygen is introduced into an atmosphere concentrated in methane, the ensuing chemical reaction oxidizes the methane and produces carbon dioxide and water. As the methane disappeared, the Earth's sky turned from pink to blue and global temperatures plummeted.

The Huronian Glaciation

- Rocks called tillites were deposited during the Huronian glaciation, 2.4 to 2.1 billion years ago. Oddly, some of these tillites were deposited close to the equator. Even during the last glacial period, the equator was completely free of ice.
- The Huronian glaciation was a mega-glacial period, an event when ice moved from the poles but did not stop at the tropics. It met at the tropics, creating complete ice coverage—a virtual Snowball Earth. After the ice retreated, something significant occurred: a leap in the complexity of the biosphere.
- Severe climatological disturbances stirred the brew again, greatly mixing up the oceans. This caused a massive rise in oxygen levels, to about 1 percent of the levels we see today.

Prokaryotes and Eukaryotes

- Oxygen is an energetic molecule. An environment with oxygen and creatures that can actually use that energetic molecule opens the possibility of developing more complex creatures. With the increase in the level of oxygen, we expect a leap in the rate of evolution and new life forms. Life up until this time had been prokaryotic slime.
- Prokaryotes are fairly simple life forms. Bacteria are prokaryotes. They show few internal modifications within the cell. Within a prokaryote, genetic material is randomly distributed through the cytoplasm.
- Eukaryotes, on the other hand, have complex structures within them, called organelles. The DNA of eukaryotes is nicely tidied

away in a discrete nucleus. The question is: How did life progress from the rather simple prokaryotes to the much more complex eukaryotic cells?

- The endosymbiotic hypothesis attempts an answer. For example, imagine that two prokaryotes are in an ocean. One prokaryote approaches another and attempts to engulf the other prokaryote—perhaps attempting to eat it. According to the theory, the prokaryote that is being engulfed isn't destroyed; instead, a symbiotic relation is set up between two creatures, resulting in eukaryotes.

Multicellularity and Differentiation

- Not long after the Huronian glaciation, there is evidence of the earliest multicellularity. The stromatolites consisted only of loose associations of cyanobacteria; each bacterium was an independent unit. A truly multicellular creature differentiates the functions of its cells.
- Possibly the earliest example of multicellularity is in the fossil *Bangiomorpha pubescens*, a red alga, dated to about 1.2 billion years ago. The cells at the base of these algae are clearly differentiated into holdfasts, the cells used to cement the organisms to rocks. It has also been suggested that certain areas of these algae show that certain cells have been adapted to perform specific sexual functions. There was definite differentiation within the cell structure of this organism.
- Complex cells and multicellular creatures, such as *Bangiomorpha pubescens*, most likely required elevated levels of oxygen. Elevated levels of oxygen would allow creatures to grow larger because, if creatures are multicellular, oxygen can penetrate through all the cells in the body and allow them to grow to a larger size.

The First Animal Eukaryote

- The first animal eukaryote was probably the choanoflagellate, a free-living, single-celled organism. These, in fact, closely resembled some of the component cells found in sponges. The

theory is that associations of eukaryotes, such as choanoflagellates, eventually gave rise to sponges—thought to be some of the most primitive multicellular animals on the planet today.

- Diversification of the eukaryotes and the first truly multicellular creatures occurred with 1 percent of oxygen in the atmosphere about 1.2 billion years ago. However, not until 630 million years ago did we see truly complex creatures. Why did evolution stall for more than half a billion years?

Evolution Is Stalled

- The reason evolution stalled was possibly related to the oxygen levels themselves. Perhaps they were just too low to permit diversification in the production of more complex creatures. However, it's also possible that Earth's chemistry was changed significantly by the addition of oxygen to Earth's atmosphere, leading to a sulfidic ocean.
- Oxygen in the atmosphere reacts with a certain mineral called pyrite, whose chemical formula is FeS_2 . In the presence of oxygen, pyrite oxidizes, producing sulfate, SO_4 . These sulfates are then washed into the oceans, where sulfate-reducing bacteria use it in their metabolism. As they do, they convert the sulfate into hydrogen sulfide, H_2S .
- The consequences of dissolved hydrogen sulfide in the oceans were profound; this condition reduced the solubility and availability of certain key metals, such as molybdenum and copper. These metals play vital roles in the enzymatic pathways of many organisms. It would appear that the biological innovation of photosynthesis may have ultimately held back evolution.

All Earth's Systems Are Related

- The processes described in this lecture demonstrate that all of Earth's systems—biosphere, atmosphere, geosphere, hydrosphere—are related.

- Changes in the biosphere had profound changes in our atmosphere: Cyanobacteria released oxygen into the atmosphere to at least 1 percent. This changed how minerals weathered in the geosphere: Pyrite oxidized to produce sulfate.
- Sulfate ultimately altered the chemistry of the hydrosphere by the activity of sulfate-reducing bacteria producing hydrogen sulfate. This would, in turn, have consequences in the biosphere by putting the brakes on evolution.
- In the next lecture, we'll explore how the next advance of global ice over our planet broke this stalemate and allowed for the next major innovation and leap in life's story.

Suggested Reading

Biello, "The Origin of Oxygen in Earth's Atmosphere."

Lane, *Oxygen: The Molecule That Made the World*.

University of California—Riverside, "Oxygen-Free Early Oceans Likely Delayed Rise of Life on Planet."

Questions to Consider

1. We often think of oxygen as the gas of life. Did it surprise you to learn that oxygen was potentially so dangerous to the early Earth's biosphere?
2. Find any iron object in your home. Consider that the iron in this object may have precipitated out of oceans by the activity of photosynthetic organisms billions of years ago.

Snowball Earth—Another Crisis

Lecture 11

Following the events described in the last lecture, our planet was radically altered. It had somewhat significant levels of oxygen in the atmosphere, but the biosphere had apparently stalled, perhaps as a result of the oxygen causing the erosion of pyrite and the development of the sulfidic ocean. Earth was a slime planet with some small multicellular algae. Changes would occur around 635 million years ago that might have been caused by yet another global glaciation. In this lecture, we'll ask: How could ice get all the way to the equator? How could such a mega-glaciation be stopped once it started? And how could life survive below ice—possibly miles thick—for millions of years?

The Snowball Earth Hypothesis

- As ice moves out across the land, it picks up debris and rock and freezes these into its undersurface. Some of the rocks make scour marks, creating glacial striations. If those rocks and ice move out across open water, the rocks can fall into sediments, producing the phenomenon of a glacial dropstone—a large boulder that does not belong in finer-grain sediment.
- In the 1940s, a geologist named W. Brian Harland found glacial dropstones dating to 600 million years ago on virtually every continent, including in the tropics. Using this information, Harland suggested the possibility of a global glaciation: a Snowball Earth. The Snowball Earth hypothesis, however, was rejected by much of the scientific community; the data were explained away as being caused by continental drift.
- During the Cold War, our understanding of a Snowball Earth was advanced by a Russian chemist and climatologist named Mikhail Budyko. He theorized that the cloud of ash and dust created by a catastrophic nuclear exchange would block out the Sun and create what is known as a nuclear winter.

- As the Earth became dark and cold, we would get into a positive feedback loop in which more solar radiation than the Earth could absorb would be reflected back to space. Ice would advance very rapidly to the equator and totally cover the planet. Once a Snowball Earth had been created, there was no going back. The ice would continue to reflect the sunlight back into space, and Earth would never be free of ice again.
- Joseph Kirschvink of Princeton University began investigating the Snowball Earth hypothesis using magnets. His experimental test was based on the fact that the Earth's magnetic field has lines of flux that are vertical at the magnetic poles and more parallel to the ground closer to the equator. The inclination of those lines of flux with respect to the Earth's surface can provide information on latitude and position.
- Because rocks contain iron minerals, when sedimentary rocks are deposited or basalt lava cools, those magnetic minerals align themselves to Earth's magnetic field. Their alignment preserves the inclination of the magnetic field at the time that the rock was actually formed, identifying the latitude and position of the rock. Kirschvink's magnetometer readings of magnetic inclination indicated that some glacial dropstones had indeed formed at the equator—in fact, a Snowball Earth had occurred.

Global Glaciation Advances

- Around 2.2 billion years ago, the methane blanket covering the Earth was gradually reduced through the action of oxygen produced by cyanobacteria. Because we had a faint young Sun, the carbon dioxide presence in the atmosphere was not sufficient to keep the planet warm, creating the first Snowball Earth. But that does not explain the more recent snowballs we have experienced.
- The theory is that more recent Snowball Earths were created because carbon dioxide greenhouse protection was compromised. Around 830 million years ago, the supercontinent Rodinia was fragmenting. The result was a configuration of continents grouped

around the equator and separated by ocean. That continental configuration led to the development of a particular climatological situation characterized by intense evaporation and tropical rainfall along the continental areas.

- Warm rain falling at the tropics had a profound effect on rocks. In a process called silicate weathering, carbon dioxide dissolving in rainwater formed carbonic acid. This acid reacted with the rocks, producing bicarbonate ions that were washed into the oceans. This process swept carbon dioxide from the atmosphere.
- About 723 million years ago, there was a massive outpouring of basalt lava. Given that basalt is particularly susceptible to chemical weathering, we have a further contributory factor to the massive drawdown of carbon dioxide from our global greenhouse blanket.
- As the carbon dioxide was washed from the skies, the Earth started to cool, and ice began to form and advance toward the equator.



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The current explanation of the Snowball Earth is that decreased carbon dioxide in the atmosphere caused the Earth to cool and ice to form; a positive feedback effect took hold as the ice reflected more sunlight back into space.

Eventually, we arrived at a positive feedback effect: More sunlight was reflected back into space than was being absorbed by the surface of the planet, and ice advanced rapidly into the tropics, sealing up the surface with a highly reflective white surface, possibly miles in thickness.

Global Glaciation Retreats

- Once the Snowball Earth effect had begun, the question is: How and why did it cease? Scientists believe that volcanoes provide the answer. Even though the surface of our planet was covered by thick ice, Earth's internal heat engine was still working. The heat generated within the Earth must escape and does so through volcanoes.
- The answer is not that lava erupts and melts the ice, however; the answer is that volcanoes emit carbon dioxide. Because the Earth was completely encased in ice, there was nowhere for the carbon dioxide to go but up; thus, atmospheric levels of carbon dioxide started to increase.
- After about 10 million years, carbon dioxide was about 10 percent of the atmosphere. (Today, it is less than 1 percent.) Those high levels of carbon dioxide caused a sizeable greenhouse warming effect, causing temperatures to swing from -122° to $+122^{\circ}$ Fahrenheit. In those temperatures, ice, even if it's miles thick, would melt in less than 2000 years.

Evidence in the Limestone

- After the Snowball Earth event, the Earth still had very hot surface conditions; there were remnants of carbon dioxide in the atmosphere, causing a greenhouse effect. Then, warm, less dense, moist air formed at the ocean surfaces and rose. As it rose, water vapor condensed, producing clouds. In fact, this would probably be the first time since the snowball event had initiated that we would have seen clouds on the Snowball Earth.
- Formation of clouds released latent heat of condensation. That further warmed the air, which continued to rise and drew in more

moist air below it into a climatological positive feedback system. The exchange of heat caused a pattern of wind that circulated like water going down the drain. We know this particular weather feature by another name: a hurricane.

- At about 112° Fahrenheit, these are not ordinary hurricanes; they are vast hyper-hurricanes. For the first time in millions of years, warm, torrential rain poured down onto the continental areas.
- This rain washed the excess carbon dioxide out of the atmosphere, which combined with water to form carbonic acid. That started to erode rocks again. Erosion of calcium aluminum silicate rocks created calcium ions, which combined with bicarbonate, producing calcium carbonate: limestone.
- If this hypothesis is correct, one of the net effects of Snowball Earth would be limestone formation. In fact, limestones have been found on the tops of cold glacial sediments.

Life Survives

- How could life survive below miles-thick ice for millions of years? Photosynthetic creatures evolved billions of years ago, and evolutionary evidence suggests that they evolved only once. The science journalist Paul Hoffman has theorized that ice in the ocean and ice on land move in slightly different ways. Where ocean and land meet, tension cracks open up in the ice. It's possible that these tension cracks created oases of light that filtered down to the ocean floor and allowed the continued existence of photosynthetic creatures.
- Other theories about the survival of life under the ice suggest that, rather than a Snowball Earth, we had more of a Slushball Earth. In other words, there were still areas of open ocean—areas where photosynthetic life could exist.
- The existence of subglacial lakes could also explain how photosynthetic life survived. Lakes that exist under even vast

thicknesses of ice are not really quite as sterile as we think. Further, ice that cools slowly can be very pure and glass-like; it can allow sunlight to penetrate right to the bottom of the ocean or lake floor. Such areas can quite adequately support a photosynthetic bacterial population.

Evolution Resumes

- After the snowball, photosynthetic algae were released into warm oceans. There was a massive rise in temperatures. The hyper-hurricanes mixed up the oceans and caused torrential tropical rains, which washed erosion products and nutrients from the continents into the oceans.
- After the release of nutrients into the warm ocean bath, there was a proliferation of cyanobacteria—pond scum—and because of that, a leap in oxygen. The oceans turned green.
- This burst of photosynthesis introduced even more oxygen into the Earth's atmosphere and ocean systems. Because these conditions are not favored by sulfate-reducing bacteria, their reign over much of the ocean was over, ending the sulfidic ocean. Because production of hydrogen sulfide was halted, key elements, such as molybdenum and copper, that are crucial for enzymatic pathways were suddenly available.
- The theory is that all these events released the deadlock on evolution, which now proceeded to produce larger and more complex life forms. As new life forms evolved, all other major Earth systems were affected. The Snowball Earth effect provides a dramatic example of how change in one system can have a tremendous effect on all the other systems around it.
- The ice permitted the next great leap in evolution. Up to this point, Earth had been a slime ball, teeming with pond scum. Now it was filled not with algae or small protozoans but with a vast array of diverse and interesting creatures. We will meet some of these creatures in the next lecture.

Suggested Reading

Hoffman, *Snowball Earth* (website).

Walker, *Snowball Earth*.

Questions to Consider

1. As a result of the current state of the Earth system and the feedback mechanisms that are in place, it is unlikely that such a dramatic global event as a Snowball Earth could ever happen again. Do you think this is a valid point of view or complacency?
2. Is it possible that catastrophic events are a vital part of the evolution of the biosphere?

Metazoans—Life Grows Up

Lecture 12

After the Snowball Earth event, oxygen was freely available for the first time, increasing the potential for life forms to become bigger and more differentiated. The stage was set for multicellular life forms. In this lecture, we'll look at the evidence we have for multicellular creatures and why and how creatures increased in size. We'll theorize about the nature of the first broad animal ecosystem and what would bring an end to it.

Why Be Big?

- Why did animals evolve to larger forms? Evolution does not happen without a purpose: There must be an advantage to growing larger. After all, being small had been a successful strategy. The majority of the biosphere's mass was still microscopic compared to creatures that lived on the surface of the planet.
- Larger size permits a creature to physically interact with its environment. For example, amoebas can move around a bit, but in general, they are at the mercy of water currents. Larger creatures are much more in control of their own destiny and can physically alter their environment.
- A larger creature can also differentiate in specialized functions and perform more complex activities. These specialized functions increase the creature's ability to exploit varied opportunities and enhance its chances of passing on its genes to the next generation.
- Finally, multicellular creatures can replace their damaged components. They are not reliant on just one unit.

The Role of Oxygen

- Oxygen levels had risen from 1 percent to about 10 percent of current levels by the end of the last Snowball Earth, around 635

million years ago. This rising oxygen level was associated with the development of something very important: O₃, or ozone. Ozone blocks ultraviolet radiation and shields the planet's biozone, which creates a condition conducive to larger associations of cells in shallower water, where there are many food resources.

- Another benefit of oxygen is that animals need relatively high levels of oxygen to form collagen. Collagen, a net of proteins, is the scaffolding that animals use to build bigger bodies.

Evidence of Diversification

- According to Darwinian evolution, there should be a chain of increasingly more primitive creatures going back into prehistory—a fossil record back to some sort of simple common ancestor. But in Darwin's time, no such fossils had been found; in fact, the appearance of large creatures was so sudden and dramatic that early geologists started a new group of periods, beginning with the Cambrian, that is called the Phanerozoic. This word means "abundant life."
- Those early ancestors have now been found. The tiny fossils, less than 0.03 inches in diameter, are from the Doushantuo formation of southern China and date to 635 to 551 million years ago. The sediments in the Doushantuo formation were deposited in a series of lagoons that developed as sea levels rose following glaciation.
- The fossils have been preserved by a process called phosphatization—an atom-by-atom replacement of the original material by phosphate. The preservation is extraordinary; it goes down to the very cellular level. The fossils are thought to include a variety of creatures: fossilized algae, acritarchs, seaweeds, sponges, and primitive corals. Some scientists suspect some of these structures belong to the bilateria.
- Bilaterians represent a broad grouping within animals that includes everything that is not a member of the cnidaria (corals and jellyfish). If the fossils are indeed bilateria, this is some of the

earliest evidence we have that diversification within animals had occurred long before the Phanerozoic eon.

Precambrian Fossils

- Before the Doushantuo discoveries, we had earlier evidence of animals. Alexander Murray, a Scottish geologist, used a fossil called *Aspidella* to correlate the rocks of Newfoundland. In biostratigraphy, like fossils are used to correlate between areas.
- One of the first paleontologists of the Geological Survey of Canada, Elkanah Billings, suggested that *Aspidella* could be from a period below the Cambrian—that is, the Precambrian. The scientific community rejected that theory because the existence of Precambrian fossils was considered impossible. In fact, in some scientific circles, all the rocks below the Cambrian were called Azoic, meaning “without life,” as opposed to Phanerozoic.
- The story then moves to Australia, where Reginald C. Sprigg, a mining geologist exploring the Ediacara Hills in southern Australia, saw some interesting structures on the underside of sandstone beds. Because he was in Precambrian rocks, he was somewhat surprised to find a rich fauna full of strange disk-like creatures, some of which resembled jellyfish and others that were segmented, like worms.
- It would take discoveries in the United Kingdom to convince the scientific community that Precambrian fossils existed. In 1957, Roger Mason discovered such a fossil in Charnwood Forest. Because Britain was widely mapped geologically by that time, the rocks these fossils came from were clearly Precambrian. These fossils are named *Charnia masoni*—*Charnia* for the Charnwood Forest and *masoni* for the discoverer.

The Ediacaran Period

- We now have evidence of Precambrian fauna. *Charnia masoni* is part of what is called the Ediacaran fauna. It has been found in 30 localities on five different continents and comprises at least 100 species.

- These are not just isolated creatures; they represent a morphologically diverse assemblage of life. They appear about 580 million years ago, but they are largely gone by the base of the Cambrian period, at about 542 million years ago.
- The last part of the Precambrian that immediately precedes the Cambrian period is now named for these fauna: the Ediacaran period. Most Ediacarans lived in fairly well-lit shallow waters, but some earlier forms may not have been photosynthetic and probably inhabited slightly deeper, dimmer waters.

Defining Ediacarans

- Some scientists consider the Ediacarans giant bacteria; some claim that they are primitive fungi; and yet others suggest that they are actually a completely unknown group of animals.
- One of the reasons why there is confusion with the Ediacarans is that they look odd. With their “quilted” surface, they look a bit like an overinflated air mattress. There is no evidence of shells or internal skeletons. It would appear that they only lived on the surface of the ocean and did not channel through the sediments. That’s in great contrast to the ocean floor today, which is quite actively burrowed by worms, clams, and other creatures.
- A paleontologist named Adolf Seilacher suggested that the Ediacaran forms are not related to anything today and that we shouldn’t even try to fit them into modern groups. One indication of their unusual nature is that they are generally preserved in coarse, sandy sediments, which is extremely unusual for creatures that are basically soft-bodied with no skeletons. For soft-bodied creatures, fine-grained sediment is the best medium for preservation because it’s better for taking up an impression and increasing the possibility of getting a fossil.
- Seilacher suggested that this meant that the Ediacarans had a super-tough body plan a bit like leather, not seen in soft-bodied creatures today. This idea led Seilacher and others to propose another

kingdom of creatures; in addition to the plant and animal kingdoms, they suggested the Vendozoia to cover these Ediacaran creatures.

- However, there is another explanation for the preservation of the Ediacarans. They probably lived in environments rich in biofilms. We think that when the Ediacarans died, they fell over, and these biofilms, or mats, would cover them, protecting them and helping in the fossilization process.

Using Molecular Clocks

- Molecular biology can help trace the origin of the metazoans and identify when animals started to diversify. Consider hemoglobin, the key molecule for transporting oxygen in the blood. Although the structure of hemoglobin is very similar in animals, subtle differences exist, and those differences increase the farther back in time we go to the split from a common ancestor.
- For example, there is no difference between human and chimpanzee hemoglobin. However, there is a significant difference in the hemoglobin between humans and fish. That reflects the distance in common ancestry between fish and humans, which is much farther back in geological time than the split between chimps and humans.
- It's estimated that differences in hemoglobin occur every few million years or so; that can be used as a rough calibration to estimate the timing of divergence between different animals. Today, we use DNA and RNA differences to do this, but the concept is



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Support that the Ediacarans are primitive forms of today's animals comes from a number of specimens, including Kimberella; this slug-like creature seems to possess a radula, a specific structure for feeding seen in mollusks.

basically the same. We can estimate times of divergence using molecular clocks and then go to the hard evidence: the fossil record.

- Using molecular clocks, we can calculate the first major division of the metazoans, the split of the bilateria from the rest of the animals. The answer is a range of time, depending on what is used to calibrate the clock. If we use the slow rates of molecular evolution of the vertebrates, for example, we come up with a time of divergence about 900 million years ago—before the Ediacaran assemblages. If we use a mean bilaterian rate, we get something much more recent, 570 million years—close to Ediacaran times.

The End of the Ediacarans

- What ended the Ediacaran experiment? To answer this question, we must look at some interesting isotopic evidence.
- We find there is a sudden flush of the stable isotope carbon-12. Because photosynthesis uses carbon-12, ocean sediments are relatively enriched in the other stable isotope, carbon-13. Therefore, a negative carbon-13 anomaly suggests the sudden cessation of photosynthesis. Photosynthetic organisms are no longer taking the carbon-12 out of the oceans; perhaps there was a mass extinction event in the late Precambrian.
- Another possibility is that we are not looking at the sudden death of the Ediacarans; perhaps we are merely looking at the end of their preservation regime. The Ediacarans were still there, but they were no longer being preserved. Recent evidence, in fact, suggests that some Ediacarans survived into the Cambrian.
- As new creatures evolved in the Phanerozoic, the Ediacarans, being very fragile and subject to predation, eventually dwindled. What we will consider in the next lecture are the creatures that came next—the creatures that would drive the evolution of animals even further.

Suggested Reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Fedonkin, Gehling, Grey, Narbonne, and Vickers-Rich, *The Rise of Animals*.

Weidenbach, *Rock Star: The Story of Reg Sprigg*.

Questions to Consider

1. Was the evolution of metazoans inevitable?
2. Do you think that the origin of the metazoans lies with the Ediacarans, or do you think new discoveries will push that origin back to 900 million years?

Incredible Variety—The Cambrian Explosion

Lecture 13

During the Cambrian explosion, we see the appearance of large fossils with hard parts, such as shells and skeletons. This was an incredible time in Earth's history. The Cambrian period is characterized by the evolution of the majority of phyla that we recognize today, almost—in a geological timescale—overnight. This lecture addresses the large-scale diversification of animals during the Cambrian period and what drove this diversification.

The Roots of the Cambrian Explosion

- The roots of the Cambrian explosion stretch back into the Ediacaran. It's possible that some diversification had already occurred in that earlier period. For example, there was some evidence of biomineralization—production of hard parts, such as shells, bones, and teeth—back in the Ediacaran, although the majority of creatures were soft-bodied.
- During the Ediacaran period, we find scaffolding elements in sponges, called sponge spicules, that provide cell structure. We also find the *Cloudina*, a group of enigmatic fossils found with Ediacarans that show us that creatures were clearly starting to biomineralize. *Cloudina* also show some early evidence of possible predatory activity in the Ediacaran period.
- Even so, major biomineralization was not significant until the Cambrian period. The early geologists would use this sudden proliferation of shelly fossils to mark the base of the Phanerozoic, the time of “abundant life.”

Biomineralization and Interaction with the Environment

- According to biostratigraphy, the base of the Cambrian and the Phanerozoic is found in Newfoundland. It's here that we drive the “golden spike” to define the transition from the Precambrian to the

Cambrian period. At this time, life began to interact significantly with its environment, not just sit passively, as most of the Ediacarans had done.

- For example, the fossil *Treptichnus pedum* represents a worm-like creature burrowing through the sediment. Unlike the Ediacarans, these creatures actively interacted with the environment.
- Around the base of the Cambrian, about 542 million years ago, we start to find evidence of biomineralization: small shelly fauna. Ten million years before the first trilobites emerged, we see in some fossils the ability to secrete a small skeleton or series of armored plates.

The Trilobite

- The Cambrian period was characterized by a vast proliferation of creatures within a short geological timescale. In the final phase, in the lower Cambrian, we see large creatures with shells. The most characteristic fossil was known to Darwin and his contemporaries: the trilobite.
- Trilobites are segmented arthropods. They have a strong skeleton of calcium carbonate, which is the mineral calcite. We think that most trilobites, especially in the Cambrian, were probably deposit feeders on the sediment surface. They trundled across the surface of the sediment, shoveling it into their mouths and processing it for bacteria, algae, or other organic material.

Evolutionary Advantage of Hard Parts

- According to natural selection, there are a number of evolutionary advantages to having hard parts, such as a skeleton or a shell.
- A skeleton allows an animal to have muscles and joints, which can then move the levers in the arms and legs. This gives it greater mobility and greater ability to interact with the environment. Also, a skeleton allows the organism to develop more complex organs within itself.

- A shell offers protection against ultraviolet radiation in shallow marine environments, which are good places to find food. A shell also gives a creature, such as the snail, the ability to clamp down, seal itself to a rock, and wait for the tide to return.
- Perhaps the most obvious reason for developing hard parts is protection from predation. Because we find evidence of teeth in the earliest Cambrian explosion fauna, the evolution of teeth may have driven an evolutionary race between predator and prey. A hard shell is good protection against a predator with sharp teeth. There are other structures evolving at this time, however, that helped drive evolution and diversification.

Evolution of the Eye

- Some scientists believe that one of the driving forces of diversification was the evolution of the eye.
- The first eyes in animals were little more than what are called eye spots—concentrations of photoreceptive cells. These photoreceptive cells were capable of detecting when a light was on or off and gave some idea of the intensity of that light.
- Compressing these photoreceptor cells in a cup-like structure improves the animal's ability to determine the degrees of brightness of a light source and the direction of light, as well. If the cup evolves into more of a spherical structure, with a small hole at the top, we have, in effect, a pinhole camera. This was a vast leap in vision ability because this structure actually produced an image.
- The pinhole camera eye was found in such creatures as the nautilus, a cephalopod. A nautilus looks a bit like a squid but lives in a closed shell. The fact that it had effective eyesight meant that it could evade predators and prey effectively on its own.
- In even more advanced eyes, the hole has evolved and is covered with transparent cells to protect the eye pit. This structure helped refract light toward a developing retina, an area where

photoreceptive cells were concentrated. Further differentiation of those transparent cells led to the development of a lens, which can focus to produce sharp images.

- The possibility that eye evolution drove the Cambrian explosion was proposed by Andrew Parker of Oxford University. According to Parker, vision in predators would improve hunting strategy, which would drive prey to develop harder protection in the form of skeletons or shells. Some of the earliest creatures to demonstrate fairly advanced vision are the trilobites. Theirs is the first true eye system that we can recognize.

Eyes of the Trilobite

- Trilobite eyes, not unlike insect eyes, are compound eyes with many lenses. These lenses are unique to the trilobites; they are composed of calcium carbonate. Trilobite eyes probably could not cope too well with bright sunlight. A trilobite from the Devonian even developed a kind of sun visor over the eye, perhaps to get about in brighter conditions.
- The trilobite eyes had a double-lens structure—two lenses of different refractive indices acting in combination. Some trilobites had many small lenses; we call this the holochroal system. Others had fewer and larger lenses; this is known as the schizochroal system.
- Many early trilobites also had a conical structure to their eyes, giving them a good field of vision. Perhaps this conical eye system allowed them to exist partly buried in sediment, with just the eyes showing above the surface. Some trilobites had eyes on the top of long stalks, allowing them to peek above the surface of material on the bottom of the ocean and keep a lookout for predators.

Cambrian Phyla

- It is widely accepted that, although the Cambrian explosion had some roots in the Precambrian, it demonstrated a rapid proliferation of phyla in an incredibly short period of time, geologically speaking.

By the end of the Cambrian period, the majority of all basic body types, or phyla, that we know of today had evolved.

- Brachiopods are not so common today, but they were important in the Cambrian—more important than the clams in the Paleozoic. They look like clams, but they are not related to them at all. Clams are part of the Mollusca, a large and important group that includes snails, squids, clams, and cephalopods.
- The Arthropoda represent probably the most diverse metazoan group of them all. This group includes the insects, crustaceans, and the Echinodermata—the sea urchins and starfish.
- The Hemichordata include the acorn worms, pterobranchs, graptolites, and chordates, which include a group called the vertebrates. There is a certain interesting species within the vertebrates called human beings.
- Only the Cnidaria, the corals and the jellyfish, and the Porifera, the sponges, have been positively identified from the Precambrian. All except the Chordata and the Bryozoa emerge from this early Cambrian explosion of life.

Small Shelly Fauna

- Cambrian fauna have several well-known characteristics. In general, these were fauna that lived on or close to the surface of the sediment. Most free-moving forms, not unlike the trilobites, were likely deposit feeders, processing the ocean floor sediment for organic material or,



The trilobite was a segmented arthropod that represented the first large creature in the third phase of the Cambrian explosion.

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perhaps, algae or bacteria and passing that material out of the gut for other creatures to process.

- There were also suspension feeders, those creatures with their sights toward the water column, trying to extract microplankton or other organic material held in suspension in the water. The brachiopods were suspension feeders, as were the eocrinoids.
- The eocrinoids are relatives of the sea urchin; they have an adaptation that suggests that something important had happened on the ocean floor. They have a kind of stalk to raise them up above the sediment-water interface.
 - It's possible that by this time in the Cambrian, because of the reduction of microbial mats, the ocean floor had become increasingly soupy.
 - These stalks would allow these eocrinoids and creatures like the eocrinoids to raise themselves above this soupiness and start to exploit the water column for ocean plankton.
- The stromatolites were now pretty well restricted to either extreme environments or to the intertidal zone, which was not colonized in the Cambrian to the extent that it is today. The intertidal zone is a fairly difficult environment to live in even today. It has vast salinity changes, temperature changes, and of course, a change in water level twice a day. But in the normal shallow marine environments, most of the stromatolites that had been so common in the Precambrian period had been grazed away by the new mobile Cambrian fauna.
- In the next lecture, we'll find out how a man on a horse in the Canadian Rockies would forever change our view of the world of the early Phanerozoic.

Suggested Reading

Erwin and Valentine, *The Cambrian Explosion and the Construction of Animal Biodiversity*.

Gould, ed., *The Book of Life*.

———, *Wonderful Life*.

Morris, *The Crucible of Creation*.

Questions to Consider

1. If we were able to rerun the Cambrian explosion, would life turn out the same way?
2. If the origins of metazoans lie in the Precambrian, should this event still be referred to as the Cambrian “explosion”?

Window to a Lost World—The Burgess Shale

Lecture 14

It's difficult to decipher the ancient biosphere. There are many biases in the fossil record that can skew our interpretation of life in the past. In order to paint a better picture of prehistory, scientists turn to areas where there have been exceptional environmental situations that have allowed for unusual and unexpected preservation. Those extraordinary finds, or fossil bonanzas, are called conservation Lagerstätten. The Burgess Shale is just such a spectacular find; it provides one of those incredible and rare windows into a world that was still booming from the Cambrian explosion.

Charles Doolittle Walcott

- In 1909, paleontologist Charles Doolittle Walcott was collecting fossils in British Columbia, Canada. He was in a rather unassuming little quarry (now called Walcott Quarry). He would make a spectacular find: the Burgess Shale.
- Walcott was a remarkable man. Throughout his life, he was secretary of the Smithsonian Institution; was president of the National Academy of Sciences; served on the National Research Council; helped found the Carnegie Institute; was involved with the National Park Service; and sat on the National Advisory Committee for Aeronautics, which is now part of NASA.
- Looking for samples of fossils from Precambrian and Cambrian strata, Walcott came across a fossil unlike any he had seen before. This fossil was of the species *Marella*, or lace crab. What was remarkable about this fossil is not only that it was most rare but also that the soft parts were preserved.
- Returning to Burgess Shale in 1910, Walcott found the stratum this fossil came from, labeling it the lace crab beds after *Marella*. By 1911, Walcott had excavated a quarry that was about 60 feet long, with a floor extending some 10 feet into the hillside.

- By 1917, Walcott had amassed more than 65,000 specimens for the Smithsonian Institution. Of the 170 or more species that have been identified in the Burgess Shale so far, 100 were first described by Walcott: an amazing accomplishment.
- The work started by Walcott and continued in the 1970s by Harry Whittington, a trilobite expert at Cambridge, would paint a picture of a more colorful Cambrian than we have ever seen before—a strange world, sometimes familiar, and with 60 to 70 percent of the fauna soft-bodied.

A Portrait of the Cambrian

- Let's paint a picture of this strange and wonderful age: the Cambrian. We'll travel back in time to the middle Cambrian, around 505 million years ago, when the Burgess Shale was being deposited. At that time, the land was not mountainous, as the Rockies are today; it was a barren desert, with no grass, no moss, no trees, no birds, no insects—in effect, a sterile environment.
- The edge of North America straddled the equator. Spread out over the shallow ocean were a few islands, also barren of life. Beyond the surf line, the water changed from a pale blue to a dark purple—designating the edge of an underwater feature called the Cathedral Escarpment, a massive submarine cliff that runs along the edge of North America, reaching to Walcott Quarry.
- The waters contained the animals of the Burgess Shale. Some of them were attached to the sediment, some actually lived in it, and others moved above it. The fauna were obviously much more diverse than the creatures from the Ediacaran, who passively moved about on the surface or attached themselves to it. These new creatures interacted with and exploited their environment.

Creatures of the Burgess Shale

- The *Ottoia* was a priapulid worm, about 3 inches long. It had a long proboscis, armed with teeth, which most likely extended to grab prey. This worm lived in the sediment, probably in U-shaped

tubes, catching prey that trundled along the surface of the sediment. When the prey was consumed and passed down into *Ottoia*'s gut, additional teeth pointing downward prevented the prey's escape.

- The priapulid worm ate such creatures as hyoliths, which have been found in the worm's gut. Hyoliths have no modern descendants. They may be related to the mollusks; scientists think they lived in a little conical shell and probably moved slowly across the surface of the sediment, grazing on bacteria and algae.
- The annelid polychaete worms found at Burgess Shale were the ancestors of today's earthworms. *Canadia*, about 1 inch long, probably crawled around on the surface but may have swum in the water column, as well.
- Sponges, such as the *Vauxia*, were common in the Burgess Shale. Like all sponges, this creature sucked in seawater through the sides of its body and expelled it from a large opening at the top, trapping organic material with its cilia. Some sponges lived close to the ocean floor, but others were starting to exploit higher niches in the water column. Some of them rose to about 8 to 11 inches above the surface of the water.
- *Aysheaia*, about 0.5 to 2.5 inches long, is a member of the Onychophora, or velvet worms. We often find *Aysheaia* associated with sponge spicules; thus, it is speculated that *Aysheaia* ate sponges.
- In addition to these creatures, in the Burgess Shale are found various brachiopods, algae, comb jellies, sea pens, sea anemones, mollusks, echinoderms, and some of humans' very early ancestors: the chordates. But probably the most impressive and most dominant representatives of the Burgess Shale are the arthropods.

Arthropods in the Burgess Shale

- The most common arthropods in the Cambrian were the trilobites. Although trilobites are found in the Burgess Shale, that formation

includes a much greater diversity of arthropods than we usually find in other deposits.

- *Marella*, Walcott's lace crab, was about 0.5 inches long and was present in large numbers in the Burgess Shale. These creatures probably swam or crawled on the ocean floor, seeking out organic debris and small creatures to eat. They had an odd kind of bristlelike appendage at the front that was used to sweep material into their mouths.
- *Canadaspis* was possibly the ancestor of many of the crustaceans that would follow.
- *Sanctacaris*, about 2 to 3.5 inches long, most likely was a predator. An active swimmer, it was the ancestor of horseshoe crabs and spiders.
- *Sidneyia*, about 2 to 5 inches in length, was one of the larger arthropods from the Burgess Shale. *Sidneyia* was most likely a carnivore, eating hyoliths and probably the occasional trilobite, as well.

The *Problemsatica*

- Another feature of the Burgess Shale was a group of creatures called the *Problemsatica*. We cannot place them adequately or with great confidence into any defined group. Nevertheless, they are remarkable creatures.
- *Opabinia* had five eyes on its head; on the front of its head was an odd trunk, at the end of which was a grasping claw. It probably swung by the undulations of lobe-like segments at the sides of its body.
- *Anomalocaris* reached lengths of 20 inches. It was definitely the *Tyrannosaurus rex* of the Burgess Shale. Its shrimp-like legs are grasping appendages at the front of the head.

Environment of the Burgess Shale

- The environment of the Burgess Shale was an unstable one, subject to occasional earthquakes that caused movements of sediment under

the water. These are called turbidity currents; these currents would push creatures rapidly into areas that were deeper and contained less oxygen.

- In the process, a great deal of sediment was transported, which would pass up into the water column and then settle back down slowly, covering all the dead creatures that had been transferred into the low-oxygen environment. Two effective ways to advance the process of fossilization are to remove the oxygen and quickly cover dead organisms.
- The survival of the Burgess Shale, however, was really something of a miracle. It was formerly deposited in a fairly deep oceanic environment. The sediments that once made up the Burgess Shale were involved in mountain-building processes—the collisions of continental masses that raised the ocean bed to great heights. When that happened, rocks were very often cooked and metamorphosed, which can easily destroy fossils.
- But the Burgess Shale was lucky. It was transported from areas of intense deformation along low-angled faults called thrusts to its present location, where it escaped intense deformational processes.

Evolutionary Experimentation

- What scientists believe happened during the Cambrian is a situation in which the genetic rules that define a creature were not so firmly established. Perhaps that could account for all the *Problematica*—those strange creatures that do not seem to fit into any group.
- We see this kind of flexibility in form in the echinoderms, as well as the arthropods. Echinoderm genetic rules dictate that they have fivefold symmetry, or symmetries in multiples of five—like a starfish or sea urchin. But consider the *Helicoplacus* and Homalozoa. Both these creatures are echinoderms, but both are very different from the echinoderms we see today.

- Today, the genetic rules that govern the organization of the animal—the number of digits, the location of the eyes, feet at the ends of legs—are controlled by Hox genes. Hox genes are pieces of our genes that act like failsafe mechanisms. They ensure that the proper body plan will be followed.
- It's possible that back in the Cambrian, there were fewer failsafe genes; the result was that more bizarre forms could come to term and be expressed. It's likely that most wouldn't have survived, but it's possible that there might have been some viable forms that might explain some of these odd species that we see in the Cambrian. This explains why the Cambrian is sometimes described as a period of great evolutionary experimentation.
- Before we go into detail about the development of the Earth's biosphere, in the next lecture, we'll deal with some of the fossils that tend to get forgotten along the way.

Suggested Reading

Gould, *Wonderful Life*.

Morris, *The Crucible of Creation*.

Yale University, “Fossil Find Fills in Picture of Ancient Marine Life.”

Questions to Consider

1. Imagine traveling 500 million years into the future and studying the fossils that represent our current period of geological time. Given the bias that occurs in the fossil record, what impression would you gain of life from our period?
2. Does it surprise you to learn that all the diversity around us today is, essentially, variations on the basic body plans that were established during the Cambrian?

The Forgotten Fossils in Earth's Story

Lecture 15

Much of the literature on fossils has a kind of cultural bias. The emphasis is on the vertebrates—creatures with a backbone. Another bias is in favor of the land creatures over fish. Plants also get short shrift, yet plants have been a vital component in the evolution of the Earth's system. This lecture will redress that imbalance. We'll focus on invertebrates and examine an important component of the oceans: the reefs. For that, we need a basic understanding of micropaleontology.

The Evolution of Reefs

- Ocean reefs are remarkable formations. Consider the Great Barrier Reef in Australia. Its individual components are so interconnected and the system so complex that the reef could be considered as a single living creature—a superorganism. It stretches for about 1600 miles and covers 133,000 square miles in area. In it are 400 types of coral and roughly 1500 species of fish. The reef has at least 4000 types of mollusks and a host of vertebrates, arthropods, and echinoderms and probably a number of other creatures that are yet to be described.
- Although not technically reefs, the first buildups of organisms were the stromatolites. The Precambrian stromatolites were some of the largest life structures. They reached a peak of diversity about 1.25 billion years ago. In the Cambrian, the stromatolites became restricted to areas of low oxygen, high salinity, and the intertidal zone. They were grazed away by the new Cambrian form and the more normal marine environments. Today, the stromatolites are generally found only in extreme environments.
- The first true reefs built up in the Cambrian. They were not created by corals, however, but by creatures called archaeocyathids, closely related to sponges. These reef builders formed some important structures in the oceans, but they steadily declined toward the

end of the Cambrian, possibly from competition from other types of sponges. Not until the mid-Ordovician would we see the next development of reefs.

- During the mid-Ordovician period, there was a proliferation of corals—extinct forms, such as rugose and tabulate corals. Rugose corals formed in a number of ways. Solitary forms were composed of a number of layers; compound, or colonial, corals were all bound together in a mass. Tabulate corals were exclusively colonial. With the sponges and sponge-like creatures, such as the stromatoporoids, tabulate corals formed extensive tropical reefs throughout the lower Paleozoic.
- By the Devonian, the reefs had become very large formations, perhaps rivaling the Great Barrier Reef today. There was a massive reef near the equator in Gondwanaland—the old name for a part of the continent that is now in western Australia.
- The ancient ocean reefs were hotbeds of evolution. They contained an incredible diversity of corals, various invertebrates, brachiopods, clams, and vertebrates, such as early sharks and fish. There was always an explosion of life around these structures.
- There was always a deadly game going on, as well: predator versus prey. It is probably because of this richness in diversity and availability of opportunity that evolution fast-forwards in reef systems.

Permian Reefs

- Reefs would come and go in the Paleozoic, but one of the most recognized fossil reefs is found in the Guadalupe Mountains: the Capitan Reef. This reef is from the middle Permian period, about 200 million years ago, a time when all the continents were grouped together into Pangaea.
- The Capitan Reef is one of the most well-preserved fossil reefs in the world. The limestone that formed the reef framework at the central portion contained a wealth of creatures, such as algae, sponges, and colonial animals called bryozoans.

- Because the back part of the reef was relatively calm, it contained depositions of fairly fine sediments: muddy, calcium carbonate-rich sediments. The water was most likely stagnant with a very high salinity.
- High concentrations of magnesium developed in these stagnant waters. This meant that much of the original calcium carbonate sediment was changed into another carbonate mineral called dolomite. Some of the calcium was replaced by magnesium in the crystal structure.
- Permian reefs were very complex. They were mostly composed of sponges with calcium carbonate skeletons. But by the end of the Permian, the reef, the majority of the reef-producing organisms, and in fact, most of life at that time would perish. We will see why in a later lecture.

Invertebrates: The Trilobites

- Invertebrates—animals without a backbone—make up more than 95 percent of all animal species. They provide invaluable information about the diversity of environments and about changes to those environments.
- Trilobites were some of the most common of the arthropods. They had three parts: the head, or cephalon; the body, or thorax; and the tail, or pygidium. The trilobite's skeleton was made of calcium carbonate, but because it was an arthropod, it had to molt in order to grow. This most likely explains the high abundance of trilobite fossils.
- Trilobites evolved rapidly, and they are extremely useful for biostratigraphy in the Cambrian. In fact, they are used to divide the Cambrian into five stages. They lived close to the ocean floor, scavenging and processing sediment for organic debris.
- Trilobites were a very successful group of creatures, in part because of the evolution of eyes. But unfortunately, they would all be

extinct by the end of the Permian, in the same event that killed off the Permian reef faunas.

Invertebrates: The Echinoderms

- Another fossil group often overlooked were the echinoderms. These included the starfish, sea urchins, and crinoids. Although crinoids are often called sea lilies, they were not plants.
- The crinoid, like the trilobite, was composed of calcium carbonate; its stalk was formed of disks called columnals. Its arms gathered food and particles in the water and passed them into its mouth.
- By the middle Paleozoic, crinoids formed vast meadows; their disarticulated plates and other remains formed very thick sediments. They were also important because the small gaps between the columnals in the sediment acted as perfect hiding places for oil.



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The echinoderms include starfish, sea urchins, and crinoids; the long arms that developed on these creatures probably helped them gather food and particles in the water.

Invertebrates: The Brachiopods

- About 251 million years ago, a type of shellfish dominated the ocean floor in the same way that clams do today: the brachiopods.
- Although they resembled clams, brachiopods had a very different biology. They had a feeding organ called a lophophore, containing a ring of cilia that they used in suspension feeding. Most of them lived on the ocean floor, sometimes attached to the floor by a fleshy stalk called a pedicle.

- After the Permian, the brachiopods were mostly replaced by the bivalves, the true clams. The bivalves themselves were an incredibly successful group. They spread all across the ocean floor, but unlike the majority of the brachiopods, they also exploited the ocean floor by boring deep into the sediments.

Invertebrates: The Mollusks

- An example of an ancient bivalve was the Jurassic oyster, or the *Gryphaea*. Bivalves are members of the mollusk phylum. The mollusks are an extraordinary group that includes the snails, gastropods, and cephalopods (squid, cuttlefish, and octopus). There were some cephalopods in the Burgess Shale faunas, but they became common in the Ordovician.
- Cephalopods were an important component in the Mesozoic oceans, 251 to 65 million years ago. A particularly common form was the ammonite, basically a kind of a squid in a coiled shell. Some ammonites were very small, and some could be up to 6 feet in diameter.

Micropaleontology

- We are surrounded by tiny life—think of pollen on land or plankton in the ocean. Microscopic animals are vital to the Earth's system, as they often form the base of an ecosystem, supporting all higher life. Remove the base of that ecosystem, and the rest of life comes tumbling down.
- Some of the earliest microplankton were organic-walled creatures called acritarchs. They were somewhat enigmatic but were probably part of a life cycle of the flagellated algae—a resting stage that produced a structure called a cyst. These cysts often demonstrated a hole in the side, showing where the creature escaped from its cyst and returned to active living.
- Acritarchs were about 15 to 80 microns in size, and they date from about 400 million years ago. To give an idea of the scale, one

micron is one-millionth of a meter. A human hair has a diameter of 20 to 180 microns.

- Possibly related to the acritarchs were the dinoflagellates. They were important components of more modern microplankton. Microfossils called chitinozoans were a little larger than acritarchs, but were still very small, ranging from 60 to 200 microns in size. They existed from the Ordovician period to the Devonian, 488 to 359 million years ago.
- The chitinozoans possessed an organic wall, made of a chitin-like substance, similar to fingernails. They were in the form of vases, sealed at one end by a lid or a simple plug. They were sometimes associated in long chains, with the lid of one attached to the base of another. Some scientists have speculated that the chitinozoans were the eggs of some other animal.
- This lecture has painted a rosy picture of the evolution of life—always onward and upward. But life has not always been so easy. The biosphere has taken hard knocks at times, and in the next lecture, we'll see how the biosphere took a severe downturn.

Suggested Reading

Armstrong and Brasier, *Microfossils*.

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Fortey, *Trilobite*.

Questions to Consider

1. When trying to describe past ecosystems that can be very different than those of today, are such terms as “reef” unhelpful?
2. Is it true that we often neglect to consider the considerable importance of the microscopic world not only in the past but also in the present?

Introduction to the Great Mass Extinctions

Lecture 16

The history of life has not always been one of steady increase, onward and upward. At times, the tree of life gets pruned—sometimes drastically. This lecture examines the phenomenon of mass extinction, the differences between background extinction and a mass extinction event, the criteria for a mass extinction, and the number of large-scale extinction events that have occurred over the past 500 million years. We'll look at what can cause a crisis in the biosphere and speculate whether there is a regular periodicity to mass extinction—a ticking time bomb.

The Reality of Extinction

- Species go extinct all the time. More than 99 percent of the species that once existed on Earth are now extinct. Even though Earth's history has seen many extinctions, our biodiversity has stayed fairly even, with extinctions matched by the evolution of new forms.
- There is a crucial difference, however, between background extinction, in which certain creatures go into extinction for various reasons, and mass extinctions, times when the biosphere sees the sudden destruction of vast numbers of species.

Subdividing Geological Time

- The health of the biosphere is generally measured in terms of the number of species it supports. Thus, it is important to examine how biodiversity changes over geological time.
- Broad changes in biodiversity help us subdivide geological time itself. The geological timescale is split into broad stages. Geologists haven't just randomly selected these stages; instead, they represent characteristic biospheres. The periods themselves are grouped into broader eras—for example, the Paleozoic, followed by the Mesozoic, followed by the era in which we live, the

Cenozoic. Each of these timescales is characterized by groups of distinguishing fossils.

- When cataloguing fossils, early geologists realized that something very dramatic had happened to life on Earth between different geological periods. For example, there were substantial differences between the creatures in the Triassic and those in the Permian.
- In effect, these early geologists were starting to pinpoint some of Earth's great crises, those mass extinction events that are characterized by extreme turnovers in species. A full understanding of these broad diversity changes, however, had to wait for the theory of plate tectonics.

Continental Fragmentation and Biodiversity

- In the 1970s, it occurred to two scientists—J. W. Valentine of Berkeley and E. M. Moores of the University of California in Davis—that the new theory of plate tectonics could explain changes in diversity over time. Continents drifting around the surface of the planet would affect the climate and food supply of creatures, would bring species into direct competition, and would isolate some species.
- Graphically plotting global biodiversity against the relative fragmentation of the continents, we see the greatest biodiversity during times of greatest continental fragmentation. This makes sense: Times of the greatest fragmentation will see the greatest climatic variation and the greatest



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Marsupials in Australia illustrate the idea of evolution in isolation that might be caused by fragmentation of the continents.

possibility of evolution in isolation. Therefore, biodiversity is likely to be higher during those times.

Cycles of Biodiversity

- A brief tour of biodiversity over the past 750 million years starts with the supercontinent Rodinia. This continent fragmented about 750 million years ago, following the last Earth snowball. Fairly soon after the fragmentation of Rodinia, the remarkable Ediacaran fauna arose.
- Fragmentation continued through the Lower Paleozoic, when a series of new continents emerged, with shallow tropical seas around their margins. The deep oceans between the continents acted as a barrier for many marine forms, as well as a climatic barrier. As a result, independent evolution and biodiversity escalated at this time.
- During the Upper Paleozoic, the fragmentation of the continent of Rodinia started to reverse, and amalgamation of the continents began. Associated with that time was a diversity fall, in addition to a few small extinction pulses.
- At the end of the Paleozoic era, which was the Permian period, we see the consolidation of another supercontinent, Pangaea. At that time, there was a massive drop in global biodiversity. In effect, everything was in direct competition. As Pangaea fragmented through the Mesozoic, diversity increased.
- Today, the continents are as dispersed as they have ever been, and we have unique ecosystems existing on the many fragmented continental areas; thus, biodiversity is considered to be high.

Defining Mass Extinctions

- The diversity changes associated with continental drift are slow. Earth's history, however, has seen rapid and sudden drops in diversity: mass extinction events. These are not entirely related to geographical isolation or amalgamation of continents. For mass extinction events, we have to look for other factors.

- One of the criteria for defining a mass extinction is severity. In a minor mass extinction event, 20 to 30 percent of species go into extinction. In an intermediate mass extinction event, 50 percent of species go into extinction. In a major mass extinction event, 80 to 95 percent of species are gone from the biosphere—very frightening levels indeed.
- Another criterion here is extent. A mass extinction extends across a wide range of ecologies—not just in coral reefs, not just in tropical rain forests, but everywhere, from the Amazon to the Great Barrier Reef, from the tops of mountains to the bottom of the oceans. It must be a global signature.
- Finally, in defining a mass extinction, we also look at timing. A mass extinction is short and sudden—less than a million years. Remember, we are talking deep geological time here; in 4.54 billion years of Earth history, a million years is “sudden.”
- Applying these criteria to the past 500 million years, we get the “big five”: mass extinction events that occurred in the Late Ordovician, Late Devonian, Late Permian, Late Triassic, and—perhaps the most infamous one because we lost the dinosaurs—the Cretaceous–Paleogene, called the K-P event.
- Some scientists suggest that today we are losing species at an unprecedented rate—about 140,000 species every year—and that we could be in the sixth mass extinction event. If that’s true, it started about 10,000 years ago with the disappearance of the megafauna: mammoths and saber-toothed tigers.

Causes of Mass Extinction

- Biological causes have been proposed to explain mass extinction. For example, an extinction may have been caused by competition between creatures occupying the same ecological niche. Perhaps they were brought together by continental drift, they competed for resources, and only the most adaptable survived. In other words, there were winners and losers.

- Another possible cause of mass extinction is generated by the Earth itself. Tectonic plates and continents moving around affected weather patterns and generated volcanic activity. Changing the configuration of the oceans altered ocean circulation patterns and the productivity of the oceans. These Earth processes had major global warming and cooling effects.
- The most dramatic cause of mass extinction is an extraterrestrial impact. When an immense rock is hurled onto the surface of the Earth, there will be serious environmental implications.
- The most reasonable explanation of mass extinction events, however, is a combination of many factors that all went wrong at the same time, to such an extent that the biosphere could not adapt.

A Ticking Time Bomb?

- An important question is whether there is a regular periodicity to mass extinction events. Is the Earth's biosphere subject to a ticking time bomb?
- To answer this, in 1984, David Raup and Jack Sepkoski of the University of Chicago examined the paleontological record of biodiversity and applied various statistical techniques to account for imperfections in the fossil record.
- They came up with this conclusion: Every 26 million years or so, biodiversity took a serious downfall. They looked at whether there were any plate tectonic features or climatological effects that had a 26-million-year periodicity but found none.

The Oort Cloud

- Raup and Sepkoski then suggested that the 26-million-year periodicity might be related to the Oort cloud, a cloud of comets in the outer reaches of our solar system, almost a light-year away from our Sun. The Oort cloud consists of the material left over after the development of our solar system. The scientists speculated that comets emerged from here and fell into the inner solar system.

Some of those comets crossed the orbit of Earth, causing extinctions or downturns in the biosphere every 26 million years.

- It was speculated that, every 26 million years, something happens to the Oort cloud—probably some sort of gravitational effect—that causes comets to fall out of that weak orbit around the Sun and start to careen toward the center of the solar system. The question is: What causes that gravitational effect?
- Raup and Sepkoski suggested that perhaps our Sun has a companion sun called Nemesis. Dual star systems are not uncommon in our galaxy. Another possibility is that a black hole created a singularity. A third possibility is that a massive planet exists just inside the Oort cloud; every 26 million years, its orbit brings it close to the Oort cloud, causing gravitational effects.

The Milky Way Theory

- Raup and Sepkoski decided to take an even larger perspective: our galaxy, the Milky Way. The galaxy isn't static; it slowly rotates. About every 225 million years, it completes a full rotation. The galaxy is not a flat pancake of stars either. Looking at a cross-section of the galaxy, we see that it has a definite thickness, and there is an invisible line running through the galaxy that we call the galactic plane.
- Our solar system not only moves around in the galaxy as it spirals, but it also moves up and down through the galactic plane. Every 26 million years, it's right in the middle of the galactic arm of the spiral—where we have the greatest concentration of material and, therefore, the greatest potential for gravitational effects. It would appear that every 26 million years, we get a hammering.
- When were we last in the middle of the galactic arm? The answer is about a million years ago. This proposed cycle is still very much a matter of debate. But mass extinction events have occurred for various reasons, including impacts.

- In the next lecture, we'll discuss the first major extinction event, which occurred during the Phanerozoic eon at the end of the Ordovician period.

Suggested Reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Foote and Miller, *Principles of Paleontology*.

Hallam, *Catastrophes and Lesser Calamities*.

Questions to Consider

1. Can you imagine what your neighborhood would look like after a 30 percent reduction in the number of species?
2. Mass extinction events represent catastrophic periods of Earth's history. Could they also be viewed as necessary and beneficial?

The Collapse of Earth's First Eden

Lecture 17

The Middle Ordovician period saw a proliferation of life forms that some say was almost as spectacular as the Cambrian explosion that preceded it. Creatures moved into different levels of the ecosystem. They burrowed deeper; they grew higher above the ocean floor. That flowering of life, however, was cut short by the Ordovician mass extinction event 488 million years ago. This lecture examines what the Ordovician world was like and what caused the mass extinction event that devastated it.

The Rise of Graptolites

- Graptolites were present in vast numbers in the Ordovician, during which they underwent rapid diversification. Graptolites were colonial organisms. In the Cambrian, they tended to be mostly stuck on the ocean floor, sessile; in the Ordovician, they adopted more of a planktonic lifestyle in the water column.
- Graptolites died and sank in vast numbers, sometimes almost completely covering the deep ocean floors. They evolved many short-ranging forms, which defined short packets of geological time. Because they were planktonic, they had a wide distribution, as well.
- These factors make them the kings of correlation and biostratigraphy in the Ordovician. There's a very fine-scale, high-resolution subdivision of the Ordovician based on the evolution and extinction of graptolites all the way through the period.

The Biosphere Interacts

- In the Ordovician, creatures began to chew through the sediment and churn it up a bit, not just to lie passively on the ocean floor, as the Ediacarans had done. The biosphere started to seriously interact with the rest of the Earth's system.

- That process went into high gear during the Ordovician. The Ordovician saw increases in burrowing bivalves, as well as certain trilobites. But it wasn't just the churning activity within the sediment that characterized this period; the Ordovician saw development above the sediment, as well.
- Colonies of creatures began to grow upward. For example, crinoids started to develop extensive communities, their stalks getting higher and higher, lifting them above the Ordovician ocean floor. This was also the time of the first true tropical coral reefs; tabulate and ghost corals were common in the Ordovician.
- The Ordovician was a period of continental fragmentation. The large block called Gondwanaland comprised parts of Africa, South America, Antarctica, India, and Australia. Laurentia comprised much of North America. Baltica formed much of northwest Europe; Avalonia comprised southern Britain, Atlantic Canada, and the East Coast of the United States. These were all the fragmented remnants of Rodinia, which had been splitting up since about 750 million years ago.

The Earth Turns Cold

- The Ordovician was a tropical paradise. Life was diversifying and spreading all through this period in a wonderful greenhouse world. But things would start to go wrong for this paradise—and very rapidly.
- The continental mass called Gondwanaland started to move closer to the South Pole. Temperatures dropped, and ice started to form. The amount of ice on Gondwanaland started to grow with each winter, and the continent ultimately became completely icebound.
- Even today, the presence of ice is recorded in glacial features in the African Sahara. Note, however, that this was not a snowball event. The paleomagnetic evidence in the Sahara rocks shows that these rocks were definitely at the South Pole when the glacial features

were formed. This is an example of how glacial features were moved by plate tectonics to a now-warmer place.

- Another way of reading the onset of this glacial period is through isotopic evidence. Like carbon isotopes, there are oxygen isotopes, as well. The lightest, oxygen-16, is the most common; there is a smaller proportion of oxygen-18 and an almost negligible proportion of oxygen-17 in the Earth's system.
- Water, with the light oxygen-16 isotope, is preferentially evaporated. During the glacial period in the Ordovician, however, that light water was trapped in glaciers; it could not get back to the oceans. Therefore, there was a relative enrichment of the heavy isotope, oxygen-18, in the oceans. This signature was recorded in the chemistry of creatures that secrete shells. The isotopic shell data show that this glacial period was short—no more than 1 million years in duration.

The Oceans Cool

- The extinction started in the last stage of the Ordovician—a stage called the Hirnantian. It was about 1.9 million years long and took place 445 to 443 million years ago. By the time it had finished, as many as 85 percent of all species were gone.
- That was a significant blow to the Earth's biosphere. The first pulse started around 445 million years ago, and it was severe in reef faunas and anything adapted to warm water. Fifty out of the 70 genera of tabulate and rugose corals suddenly went extinct.
- Cooler-water forms started to migrate toward the equator, chasing the warmer water. But the tropical forms really had nowhere to go—apart from extinction, unfortunately.

Sea Levels Drop

- Glaciation also had another effect: When water was locked in the continents, not only did the ratio of oxygen isotopes in the ocean

change, but also the water was physically prevented from getting back into the oceans. Consequently, the sea levels dropped.

- Evidence of this appeared as an erosion surface in many Ordovician sediments. Land was eroded because rivers ran across it, in effect, trying to come into equilibrium with the new lower sea levels.
- The second pulse of extinction at the end of the glacial period was related to sea levels and temperatures rising again. It wasn't as severe as the first pulse; it is speculated that it occurred in cold-adapted forms that struggled to switch back to their warm adaptations.

The Effect of Greenhouse Gases

- The Hirnantian glaciation was the smoking gun for the Ordovician extinction event. But there is a problem. Gondwanaland had moved over the South Pole some millions of years before the glaciation occurred. We are obviously missing part of the story. Something changed to move Earth into a cooling phase—not just the presence of Gondwanaland in the South Pole. One explanation was the effect of greenhouse gases.
- During the Ordovician, two continents, Baltica and Avalonia, moved toward Laurentia. There was a shrinking ocean, the Iapetus Ocean, between them. That ocean was not really shrinking, of course; it was being removed by subduction at the continental margins. As the Iapetus Ocean diminished, mountains started to rise. As those mountains rose, they were subject to fairly intense erosion.
- The erosion of rocks uses up carbon dioxide in the atmosphere through silicate weathering. Usually, the drawdown of carbon dioxide from the atmosphere by this erosion is matched by the addition of new carbon dioxide by volcanic activity. However, it has been suggested that during the Hirnantian, volcanic activity had dropped; thus, there would be a net drop in atmospheric carbon dioxide.



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The sediments around the mountain known as the Old Man of Coniston in the Lake District of England contain trilobites and graptolites, creatures that inhabited the Iapetus Ocean as it diminished.

- That meant that Gondwanaland, which was already over the South Pole and turning cold, recorded a drop in carbon dioxide levels, meaning lower greenhouse effects and lower temperatures on the planet. This was the trigger that drove the Earth into a sudden glacial episode, and that explains the lag. The carbon dioxide levels had to drop in order to trigger the glaciation event.

The Effect of Gamma Rays

- Brian Thomas, an astrophysicist at Washburn University, believes that the cause of the Ordovician extinction had a more distant and even more alarming origin: a gamma ray burst. Gamma ray bursts were first detected in 1967 by satellites searching for evidence of nuclear emissions during the Cold War. These gamma emissions weren't the product of a nuclear bomb, however; they were coming from space. Sometimes they were microseconds in length; sometimes, several minutes long.

- The longer bursts are thought to be caused by the death of a hypergiant star. Hypergiants are many millions of times more luminous than our Sun and have a life span no longer than around 3 million years. (Our Sun has a life span of about 10 billion years; we are 5 billion years in.)
- After their relatively short lives, these hypergiants die in a spectacular event—a hypernova, which releases 100 times the amount of energy released in a standard supernova. Because of the sheer mass of the hypergiant, when it dies, it eventually not only forms a black hole, but it also emits jets of plasma at nearly the speed of light. It is speculated that these jets produced the longer gamma ray bursts.
- It is thought that these gamma ray bursts then depleted ozone on Earth—the O₃ molecule that absorbs harmful ultraviolet radiation. Paleontologist Bruce Lieberman from the University of Kansas thinks that this could potentially account for the extinction in trilobites. Although adult trilobites lived on the ocean floor and had a large protective body of water above them, it's likely that trilobites had a planktonic juvenile stage that was affected by the radiation.
- Many other creatures besides trilobites would have been severely affected by increased ultraviolet levels. The gamma rays may have wiped out an entire generation of progeny and caused the extinction of many groups.

The First Mass Extinction

- The Ordovician mass extinction was the first major extinction of the new metazoan biosphere. A glaciation was a new event for this biosphere. None of the Ordovician creatures had really become preadapted to it, as later iterations of the biosphere would. As a result, during the Ordovician, the casualties for the biosphere were very high indeed.
- During the Silurian, the biosphere started slowly to recover and produce a burgeoning new world full of tropical reef systems. But a

new frontier would start to be explored in the Silurian, as well. The biosphere was looking outward from the ocean and would make a conquering move toward the land.

Suggested Reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

California Institute of Technology, “Mass Extinction Linked to Ancient Climate Change, New Details Reveal.”

Hallam, *Catastrophes and Lesser Calamities*.

NASA/Goddard Space Flight Center, “Explosions in Space May Have Initiated Ancient Extinction on Earth.”

Questions to Consider

1. Is it possible that the short amount of time our species has existed on this planet has blinded us to a universe that is less benign than we may have thought?
2. Do we look to extraterrestrial causes for mass extinctions because it is uncomfortable to think that the place we call “home” can sometimes turn against us?

Making the Break for Land

Lecture 18

This lecture discusses a significant leap in the biosphere: when plants and animals living in the oceans adapted to live on the land. There were significant obstacles to making the adaptation to land. For example, in the ocean, the buoyancy of water supports the body; on the land, creatures need a system of internal or external structures. Aquatic animals and plants can extract water and nutrients from their surroundings; land animals and plants cannot. Temperature extremes are greater in the air than in water. This lecture looks at the kinds of adaptations plants and animals made to get onto the land and the characteristics of the new terrestrial ecosystem.

Selective Advantage of Land Plants

- John Raven, from the University of Dundee, has proposed a scenario that explains how an aquatic alga adapted into a land-living plant. Imagine algae in shallow freshwater, fairly close to the land. If the algae were able to raise their sporangia above the water surface, the breezes blowing across the surface of the water would help distribute the spores and their genetic material.
- Another selective advantage driving this evolution was light. Land plants have access to sunlight for longer periods of time than aquatic plants. In water, plants are restricted in their distribution; they tend to be concentrated in an area called the photic zone—the depth to which light can penetrate the water.
- On land, it's easier to extract carbon dioxide than it is in water. Because the plants still cannot extract nutrients from the air, one of the first developments in plants that made it to land was a simple conducting strand, or piping system, to carry water to the upper parts of the plant from the lower parts.

Development of the Plant Cuticle and Stoma

- Land plants are more susceptible to dehydration than aquatic plants. The solution to plants' losing water was the plant cuticle, a waxy covering of the surfaces of the plant exposed to air. The cuticle not only reduced the effects of desiccation, but it also acted as a repellent to stop films of water from collecting on the plant. These films cut down the uptake of carbon dioxide from the atmosphere.
- The cuticle provided rigidity, so the plant could get higher. The cuticle also may have acted as a barrier to excess ultraviolet radiation from the sun.
- The problem associated with the cuticle is that now the plant cannot absorb nutrients from the surroundings. It's thought that this led to the developments of roots—specialized areas of plants that gathered nutrients from the soil and passed them up to the parts that could no longer extract those nutrients.
- The plant cuticle also prevented the plant from absorbing carbon dioxide. This probably led to the development of stomata, or pores. Cells on either side of the pore opened and closed to allow gas exchange and to protect the plant from excess water loss during warm periods.
- The stomata linked to an intercellular gas transport system between the cells, solving yet another problem—the transport of food to the roots. The plant roots, although adapted now to transport nutrients and water upward, were cut off from the light, so they couldn't photosynthesize and produce food themselves.

Vascular Plants

- Eventually, plants developed xylem, a structure of cells placed end on end to form a tube to improve the flow of water through the plant. In a process called evapotranspiration, water moved up from the root as a result of negative pressure generated by the evaporation of water on the surface of the plant. Plants with such a xylem system are called vascular plants.

- Because the evapotranspiration process created high pressures in the xylem, plants needed to strengthen and encase this system. Development of the material called lignin allowed plants to strengthen and grow even larger than the original cuticles had allowed.
- Plants developed another type of transport system within themselves called phloem, which moved products of photosynthesis, such as sugars. That was important for areas needing more energy—for example, the growing tips of plants and the roots.

First Land Plants

- The oldest land plants were from the Middle Silurian period. For example, the fossil *Cooksonia*, just over an inch tall, had sporangia, or fruiting bodies, that produced spores. *Cooksonia* had no leaves, however; it probably photosynthesized along the length of its stem. It was also linked underground by a common root structure called a rhizome.



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In making the transition to land, lack of buoyancy was a major problem for aquatic plants, along with the loss of the ability to extract nutrients directly from the surrounding environment.

- This plant was still restricted to low-lying freshwater marshlands. By the Early Devonian, *Cooksonia* had evolved xylem, cuticles, and stomata. Also by this time period, plants probably started to look fairly modern.

The Rhynie Chert

- Just as we have the Burgess Shale as an example of extraordinary preservation for the Cambrian, we have Rhynie Chert, in Scotland, for a window into the world of early developing plants in the Devonian.
- The Rhynie Chert was deposited 412 to 400 million years ago. Discovered by Dr. William Mackie in 1914, the Rhynie Chert is an assemblage of ancient plants from the Devonian period. It contains seven types of vascular plants, as well as a rich collection of other creatures and plant material, such as fungi, algae, and lichen.
- The Devonian saw plants with a significant elevation from the surface of the land. *Asteroxylon*, a lycopod, had small scales all along its length—the beginnings of leaves. *Rhynia*, at eight inches, was taller than *Cooksonia* and branched much more.
- The Rhynie Chert, an important conservation Lagerstätte, was subject to the process of permineralization—detailed preservation at the cellular level through atom-by-atom replacement of organic material. The formation was produced by the action of silica-rich hot springs killing off the Rhynie flora, but as they did, silica was precipitated on the plants and replaced some of their carbon.

Preadapted Arthropods

- Plants were the first to move onto the land. The newly established plant ecosystem, however, created a rich and diverse environment for animals to exploit. Animals had obstacles similar to plants' adaptation to land: They had to address problems of body support and breathing and problems with dehydration. Because seeing and hearing are vastly different in land and water, their senses would need to be modified, too.

- The first group of animals to move from the sea to the land was the arthropods. Arthropods were almost preadapted to move onto land. They had already developed an exoskeleton and a variety of limbs, more so than the vertebrates had at that point.
- The first arthropods to make the break for land were probably the eurypterids, or sea scorpions. A diverse group, the eurypterids were the “top dogs” of the Silurian. Related to today’s scorpion, many were predators; some species, such as *Pterygotus*, were up to seven feet long.
- It has been suggested that these creatures had book lungs—structures that modern arachnids use to breathe. Even the most terrestrially adapted eurypterid was still a fully aquatic animal, however. Perhaps they moved briefly onto land to molt and then went back into the water. They were not true land animals.

First Land Animals

- The first true land animal, discovered in Scotland by a bus driver and paleontology enthusiast, was a fossil millipede from the Late Silurian period, about 428 million years ago.
- What was significant about this fossil millipede is that it clearly possessed structures called spiracles—holes on its side that connected to a vast network of tubes that allowed air to circulate in the creature. This first air breather was called *Pneumodesmus newmani*, the oldest evidence so far of the first true land animal.

A New Ecosystem

- A new ecosystem was developing. Two categories of creatures have been preserved in the Rhynie Chert: detritus feeders, such as millipedes and springtails, who fed on decaying plant matter, and predators, such as centipedes and an extinct group of arachnids.
- Plants continued to evolve through the Devonian and develop new structures. One of the surprising new structures was secondary

xylem—or wood. Plants had become trees. The terrestrial ecosystem was set to dramatically expand upward.

- *Archaeopteris* was a Late Devonian tree about 39 feet tall. These types of plants had a profound effect on the land ecosystem. They shaded the ground below them, which created new challenges and habitats for the flora that existed below.
- *Archaeopteris* had another innovation, as well: seeds. Until plants produced seeds, vegetation was tied to the water's edge. Conditions had to be damp for sperm to swim to the egg. But in seed plants, fertilization was internal. Seeds allowed plants to colonize the barren continents.
- This was the greening of the Devonian: Plants spread across barren landscapes that were formerly only fringed with areas of green. In addition to this expansion across the landscape and the development of plants up into the atmosphere, there was a corresponding expansion of plant systems down into the geosphere.

A Second Glaciation

- Burgeoning of enhanced root systems, as well as fungi, occurred in the Devonian. Significantly, these were powerful agents of rock erosion. At this time, there was a drawdown of atmospheric carbon dioxide by plant weathering, eroding rocks. Plant roots were powerful features in the erosion landscape.
- It is speculated that this drawdown of atmospheric carbon dioxide caused global cooling toward the end of the Devonian. Tillites and other glacial features moved toward the equator on Gondwanaland. Glaciers ultimately reached about 30 degrees south of the equator—proof that overcooling had a significant effect on the planet.
- This was the second glaciation of the Phanerozoic; it also caused the planet's second mass extinction. Forty percent of the marine genera were wiped out completely. Cooling and lowering of sea levels eliminated the habitats of tropical reef fauna, including the corals.

- It's hard to imagine that the development of plants caused such a crisis. Today, plants are seen as indicators of a healthy biosphere. But perhaps certain growing pains are to be expected in the development of a new biosphere.
- By the Devonian, plants and arthropods had populated the land. In the next lecture, we'll return to the ocean, where we'll find out what happened to the vertebrates.

Suggested Reading

Cowen, *History of Life*.

Gee, ed., *Shaking the Tree*.

Questions to Consider

1. Could animals have ever made it onto land if plants had not gone first?
2. Was the colonization of the land by the biosphere inevitable?

Getting a Backbone—The Story of Vertebrates

Lecture 19

This lecture takes a closer look at our own family—the phylum chordates, which includes the subphylum vertebrates. The vertebrates are an incredibly successful group. They inhabit many environments—from the frigid poles to the scorching deserts. We find them in the highest peaks and in the deepest ocean valleys. In this lecture, we'll ask: What were the earliest vertebrates, what are the conodonts and how do they fit into the vertebrate story, and finally, what were the first fish?

Earliest Chordates

- To appreciate what vertebrates are, we need to understand the larger phylum that comprises vertebrates: the chordates. Chordates are creatures that possess a notochord, which is a rod-shaped flexible axis and support structure. In most vertebrates, this structure has been mineralized to form the vertebral column of the spine. Another typical chordate feature is the group of muscle blocks called myotomes.
- Pikaia* was one of the earliest chordates; its fossils are found in the Burgess Shale in British Columbia. Initially, it was thought to be just a worm, but its myotome muscle blocks and the long tube running down its length mark it clearly as a chordate.



The most primitive chordates living today are tunicates, or sea squirts.

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- *Pikaia* closely resembled the amphioxus, a lancelet. About 2 inches in length, the amphioxus lived buried in the sand. Its eyes peeked above the sand surface, but it could also swim if need be in open water. It possessed a notochord and myotomes and another common chordate feature: a swimming fin. Although there was some cartilage around the mouth and gill slits of this creature, it did not possess a true skeleton.

The Maotianshan Shale

- For additional examples of the earliest chordates, we turn to a Lagerstätte older than the Burgess Shale: the Chengjiang County exposure in Yunnan Province of China. This formation is significant because the fossils here are from the Lower Cambrian, 520 to 515 million years ago. That makes them 10 million years older than those in the Burgess Shale. Chengjiang is a fascinating formation because it demonstrates the speed of diversification after the Cambrian explosion.
- The rock containing the fossils is called the Maotianshan Shale. Like the Burgess Shale, it is dominated by arthropods—they represent about 50 percent of the fauna. Also in the formation are found five species of trilobite, some of which show traces of legs and antennae.
- It is estimated that one-eighth of the fauna in the Chengjiang formation were *Problematica*—creatures that really do not fit into any existing group. For example, the formation contained six types of creatures similar to *Hallucigenia*, described in an earlier lecture. Another strange creature was a member of the *Vetulicolia*, an extinct phylum of creatures divided into two parts.
- *Myllorukunmingia*, from the Maotianshan Shale, was a small creature, about the size of a paper clip, but with a distinctive head and myotomes. The creature had fins and a notochord and, unlike *Pikaia*, evidence of gill slits. It is also possible that we see the preservation of the pharynx and the digestive tract in this tiny fossil. By looking at the structure of this creature and the arrangement of

the muscles, it is speculated that it swam by flicking its body from side to side.

- Also among the Chengjiang fauna was the *Haikouichthys*, a creature about the same size as *Myllokunmingia* but slimmer. It had a definite head, and some have suggested evidence of a skull, but it had other defined chordate features similar to those found in *Myllokunmingia*. About 500 specimens of this creature have been found; thus, it is speculated that these creatures swam in large shoals.
- It is possible that some of these Chengjiang forms may represent the first true vertebrates—perhaps even the first fish. Although this subject is still debated, it is clear that our ancestors were present in the Early Cambrian.

Conodonts

- Conodonts were ancient chordates, now extinct. The fossils are toothlike structures composed of calcium phosphate, or the mineral apatite—the same composition as our bones and teeth. They were less than 0.3 inches in size and are only known from marine sediments. They first appeared in the Late Cambrian, but they were extinct by the Triassic period, about 200 million years ago.
- Conodonts are extremely useful microfossils; scientists apply them extensively in biostratigraphy. The oil industry uses them to date rocks and to provide a stratigraphic tie in searching for relevant oil strata.
- For some time, exactly what conodonts were was unknown. Initially, each conodont was given a different species name—that is, until scientists determined that the toothlike elements were associated in a symmetrical apparatus. The conodonts were thought to be individual components of an articulating assemblage.
- The answer was finally found in the Granton Shrimp Bed in Scotland—another wonderful Lagerstätte. The high salinities and low oxygen conditions in the formation killed off the creatures

fairly quickly and stopped decomposition, and its barrier deterred scavengers.

- In the fossil bed was an interesting creature, about 2 inches long, with myotomes, a notochord, a swimming fin, and two large eyes at one end. Most significantly, an associated conodont apparatus was found right by the head. It was the conodont animal. Although conodonts were not our direct ancestors—they were probably not vertebrates—they provide interesting color to that early time of the chordate evolution.

The Soom Shale

- Table Mountain in Cape Town, South Africa, has a particularly important deposit called the Soom Shale. The Soom Shale was deposited in the Ordovician period, during the Hirnantian stage—the glacial phase at the end of the Ordovician, about 435 million years ago.
- The Soom Shale was deposited in front of a retreating ice sheet. While the ice sheet was busy eroding rock, its runoff provided sediments. Because glacial periods were also fairly dry periods, winds blew silt around. Both these actions fertilized the oceans in the area of deposition of the Soom Shale, causing a bloom of microplankton.
- In the Ordovician, that microplankton consisted of acritarchs. These acritarchs sank to the ocean floor and used up all the oxygen, creating an anoxic environment in which creatures could be preserved and giving rise to another Lagerstätte.
- The Soom Shale has fossils of what are described as the oldest land plants in the world. They come from the Late Ordovician; thus, obviously, the *Cooksonia* is not the first. These plants are called *Promissum pulchrum*, meaning “beautiful promise.”
- Richard Aldridge, a well-known conodont paleontologist, realized that these were not plants; they were giant conodont elements.

Those conodonts were clearly visible—not microfossils at all. Aldridge found the animal associated with conodont elements in the Soom Shale. The conodont animal that produced the large conodont elements was possibly as long as 16 inches.

Calcium Phosphate versus Calcium Carbonate

- As our ancestors grew larger, eventually, they exceeded the notochord's ability to act as a stiffened rod against which muscles could flex and allow a swimming motion.
- The sharks were probably one of the first creatures to solve this problem. They developed cartilage in their skeletons that allowed them to grow larger. Other vertebrates mineralized that cartilage to produce skeletons of bone—calcium phosphate, the mineral apatite.
- Why they would use calcium phosphate and not calcium carbonate is an important question. Calcium carbonate is much more abundant in the oceans. It has been used successfully by many invertebrates and trilobites, corals, brachiopods, and clams.
- Richard Cowen of UC Davis, in his book *History of Life*, suggests an interesting possibility. He speculates that the phosphate skeletons in the vertebrates developed as a result of oxygen debt. As vertebrates, we are active creatures. We are prone to sudden bursts of motion, a process that breaks down sugars in our muscles faster than we can acquire oxygen. This is the process of anaerobic glycolysis. The cost of the oxygen debt is lactic acid—or fatigue in the muscles.
- As the oxygen debt is paid back, the levels of acid in the blood start to increase. That temporarily leaches calcium out of the calcium phosphate in our bones. That is not a problem; we can cope with that. But if our skeletons were composed of calcium carbonate, or calcite, the leaching would be catastrophic. In effect, the acid levels in the blood would dissolve our skeletons away. Perhaps calcium phosphate in our bones points to evidence that our ancestors were highly active creatures.

First Fish

- The first abundant fish, agnathans, appeared in the Silurian and the Devonian. Agnathans were fish without articulating jaws; fish with jaws appeared later. Rather than a rigid internal skeleton, these creatures stiffened their bodies with plates on external surfaces. They looked a bit like armor-plated fish.
- An early successful group were the heterostracans; they diversified rapidly in the Silurian, occupying numerous niches. They were found in normal marine conditions, brackish conditions, and freshwater conditions. Not strong swimmers, they probably strained microplankton from the seawater or dug in the sediment. Some had long, swordlike projections to stir up the sediment.
- Another group, the osteostracans, appeared in the Late Silurian and diversified through the Late Devonian. These were the most advanced agnathans; some reached sizes of 3.2 feet long. Some of them possessed what seem to be pressure sensors around the armored head shield; perhaps they used them to detect movement in the surrounding water. Most of them probably lived in freshwater environments.
- Although the osteostracans had some major advantages, they had a significant drawback: All they had for a mouth was a simple slit. That clearly restricted what they were able to do in the environment. For example, it would be fairly difficult to be a predator with that kind of mouth.
- The next development is the evolution of the jaws, which would take the vertebrates to the next level.

Suggested Reading

Armstrong and Brasier, *Microfossils*.

BBC News, “Oldest Fossil Fish Caught.”

Morris, *The Crucible of Creation*.

Questions to Consider

- Given the success of the vertebrates today, is it surprising that the group's origins are so humble?
- Conodonts are a classic example of a formally enigmatic fossil that is now much better understood in light of new discoveries. How many of our preconceived ideas regarding the fossil record may be overturned by similar discoveries?

The Evolution of Jaws

Lecture 20

This lecture continues our examination of the vertebrate family and investigates the crucial importance of the development of an internal skeleton. Another noteworthy milestone in the evolution of the vertebrates was the development of jaws. This development was followed by the adaptive radiation of fish, that is, the evolution of new species from a common ancestor in a relatively short period of time. We'll also explore one of the most significant Lagerstätten of fossil fish in the world: the Orcadian Basin in Scotland, dating from the Devonian.

The Search for Evolutionary Advantage

- In the Cambrian, the evolution of vertebrates was impeded by killer arthropods. In the Ordovician, the jawless agnathan fish, including the conodonts, remained less competitive compared to other creatures. The vertebrates were not especially competitive in the Silurian, either.
- What the vertebrates needed to change their position in the ecosystem was more size and strength. This called for the evolution of a more substantial internal skeleton and a jaw system. These two developments would allow vertebrates to become the sovereigns of the oceans.

Significance of the Skeleton

- The vertebrate skeleton is composed of either bone or cartilage. Cartilage is unmineralized and flexible, made up of collagen and fibers that heighten elasticity. Initially, we all had a cartilage skeleton; as the human embryo develops, however, the skeleton ossifies, or mineralizes.
- The first skeletons were probably cartilage. Unfortunately for paleontologists, cartilage rots away very rapidly compared to bone. Bone itself is composed of needle-shaped crystals of the mineral

hydroxyapatite. It forms in a network of organic collagen fibers. That's the great advantage of bone: It is strong because of the hydroxyapatite, but the collagen makes it flexible.

- Some of the oldest fish adopted a slightly different strategy: They covered themselves in outer bony plates—a kind of external rather than internal mineralization. *Arandaspis*, one of the contenders for earliest vertebrate, was covered with armored nobs called scutes. Its head was protected by a very large plate. This was an Ordovician creature, from about 480 to 470 million years ago.
- The most significant advantage to having an internal skeleton is that it enables an animal to get larger. The skeleton can grow with the animal. For example, compare human growth to that of the arthropods. Arthropods, such as the trilobites and crabs, reach an upper size limit. The size of their shells limits how much more they can grow; therefore, they have to molt. Molting is costly in energy and leaves the animal vulnerable for a period before the new shell becomes hard.
- In addition to providing support, bones also protect our internal organs. They generate and transfer forces and allow muscle movements. They provide shape to the body and allow for the transfer of sound by the evolution of tiny bones in the ear. Bones produce blood in the marrow and store vital minerals. They can also isolate toxic heavy metals and remove them from the blood. They help buffer the blood against excessive pH.

Significance of Jaws

- The development of jaws substantially impelled the evolution of vertebrates. It's likely that jaws developed as structural supports in the gill systems of jawless fish, such as the agnathans. The front sets of these supports migrated forward to become the parts of the brain case.
- It sounds counterintuitive, but it is likely that jaws did not evolve for predation; they evolved in order to aid respiration. Once

jaws had evolved, however, they could be utilized in other ways. After jawed fish evolved, they started to radiate rapidly into three major groups.

- The placoderms were the first jawed fish, most of which were predators. In addition to jaws, they also had a new innovation: a neck joint. Placoderms provided us with another first, as well—a rare fossil embryo attached by an umbilical cord to the adult. This was a fish that produced live young, an example of viviparity and internal fertilization—possibly the first example of this in the vertebrates.
- The acanthodians were less than 8 inches long and look a little more familiar than the heavily armored placoderms. It is probable that modern fish evolved from this group. They were characterized by spines on their fins and bellies. The head had forward-pointing eyes and a lateral line down the side of the body; it also had a sense organ to detect movement. The acanthodians are found fossilized in vast numbers; researchers suspect that they swam around in large shoals at mid-levels in the water column.
- The chondrichthyes include modern sharks and rays. Although the fossil record of this group is poor, a section preserving some very early forms was found in the Cleveland Shale on the south shore of Lake Erie.
- During the Upper Devonian, the bony fish with powerful fins emerged—the most common fish that we find in today's oceans. It is from this group that vertebrates would make the move onto land.

An Evolutionary Arms Race

- Interestingly, we see a pulse of evolution in the sharks matched by a pulse of evolution in the bony fish. We think what we are seeing here is an evolutionary arms race. Innovations in one group were being countered by another and pushing on the diversity of both forms of fish.



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Modern sharks and rays are chondrichthyes, the third group of fish that started to radiate rapidly after the development of jaws.

- Sharks are a very successful group. There are many different species, but they are all similar in form, shape, and body plan. Perhaps the most terrifying of all the sharks was called megalodon. It lived relatively recently, 25 to 1.5 million years ago, and may be the contender for one of the largest and most powerful vertebrate species that has ever lived.
- Megalodon was about 52 feet long and had teeth about 7.1 inches long. (*Megalodon* means “big tooth.”) The bite force generated by this creature was probably about 10 times that of a great white shark. It is thought that this creature preyed on the whales that existed at the same time.
- Megalodon became extinct as the oceans cooled and the most recent ice age began. Whales moved to cooler waters for much of the year,

but because the megalodon was most likely a tropical creature, it could not follow its prey and died out.

A Fossil Fish Lagerstätte

- The fossil fish Lagerstätte of the Devonian is the Orcadian Basin, named for the Orkney Islands in northeast Scotland.
 - During the Middle Devonian, about 385 million years ago, a continent called Euramerica developed that comprised parts of North America, Greenland, and Europe.
 - At that time, Scotland existed in a semi-arid environment south of the equator, close to a mountain belt formed from the collision of those different continental fragments. The remains of that mountain belt formed the Appalachians, the Caledonians in Scotland, and mountains in Scandinavia.
 - Where continents collide is often represented by fault lines. We can see those fault lines today in Scotland as a line of lakes that includes the famous Loch Ness. This is the setting of the Orcadian lake area. During Devonian times, as the fault moved, sedimentary basins opened up along its length, some of them filling up with sediment from the surrounding Caledonians, which were rising all around them.
- The fish fossils found in the Orcadian Basin are composed of blackened shiny apatite or sometimes isolated scales; they are commonly concentrated into beautiful fish beds. The sediments containing these fossil fish beds represent repeated cycles in sedimentary type—probably reflecting changes in the level of the lake, which itself might represent fluctuations in climate. When we study these sediments, we find that there is a prominent cycle every 25,000 years or so.

Climatic Cycles

- The climatic regimes were probably generated by long-term variations in the Earth's orbit. During times of warm climate, warm surface waters developed. These waters maintained a kind of

warm lid on the surface of open bodies of water, which were cold underneath. This boundary is called the thermocline.

- The thermocline and the lid above it acted as a barrier to circulation. The deeper parts of the lake remained cold and still. The warm surface layers of the lake, of course, were in contact with the atmosphere; thus, plenty of oxygen diffused into them.
- These conditions—a good deal of oxygen and warmth—were ideal for algae production, leading to an algal bloom. The surfaces of lakes turned green as the algae died, decayed, and sank to the bottom of the lake. The oxygen conditions that were already present within those colder waters paid a price now, however. As the algae started to decay, it rapidly used up the oxygen, causing virtually anoxic conditions and killing the fish. We call this process lake eutrophication.
- Algal blooms were probably responsible for the fish beds that we find in the Orcadian Basin. As the oxygen was used up, low-oxygenated waters would encroach onto the lake margins, causing many of the armored agnathans to die. They were swept into deeper parts of the lake by currents.
- As the hot, arid climates continued, the lake became shallower, and the cycle would ultimately end. Sedimentary structures recorded the shallower water conditions. There was evidence of fossil ripples created by surface winds moving the sediment into ripple structures. Polygonal mud cracks appeared, indicating that the water was getting shallow and evaporating away. However, the cycle repeated as wet climates returned and the lake filled again.
- Some of the fish of the Orcadian Basin lived very close to the land-water interface. They would diversify into a variety of fantastic forms. In the next lecture, we'll take a closer look at some of the bony fish, especially one that would be potentially adapted to do something very special—make a break for the land.

Suggested Reading

Gould, ed., *The Book of Life*.

Questions to Consider

1. In the moral sense, can science be bad?
2. How important do you think competition between various groups of creatures has been as a driving force of evolution?

These Limbs Were Made for Walking?

Lecture 21

Think about the incredible ease with which vertebrates move across the land—the grace of a gazelle, dogs frolicking in the park, a marathon runner. In the ancient oceans, vertebrates enjoyed the benefits of being in the water: its buoyancy, relatively stable temperatures, and no problem with dehydration. This lecture will explore how and why the vertebrates actually made it to land. To find out, we'll tackle a controversial topic: the existence of evolutionary transitional forms. We'll also examine what the first land vertebrates looked like and consider the first tetrapods as they strode purposefully across the land surface—or did they?

The “Missing Link”

- Another term for evolutionary transitional form is “missing link.” The missing link is a topic of hot debate in the study of human evolution. A crucial point here is that there is no direct link between a chimpanzee and a human being. We are not, in any way, descended from chimps. Instead, evolutionary biologists believe we share a common ancestor.
- Our common ancestor was the branching point from which the creatures that would become chimps and the creatures that would become humans diverged via numerous transitional forms. The common ancestor for chimps and humans was thought to exist around 7 million years ago. In effect, transitional forms show us that evolution happens.

Two Theories of Evolution

- There are two main theories of evolution, and their differences also have consequences for how we interpret the fossil record. The first is called phyletic gradualism, which speculates that life changes very slowly in small steps over millions of years, with species evolving slowly and gradually. The fossil record, however, sometimes shows

the sudden appearance of species. The gradualist model considers this an artifact produced by incompleteness in the fossil record.

- Charles Darwin is often cited as a gradualist, but he had noted in his writings that there are sometimes periods of little change followed by sudden rapid change. This theory is similar to the evolutionary theory called punctuated equilibrium. In punctuated equilibrium, species populations do not change much. If environmental changes favor a particular feature, however, a population will change very rapidly indeed.
- A common example of punctuated equilibrium comes from the peppered moth, a white speckled moth. Because coal smoke turned tree bark black during the industrial revolution, the peppered moth was suddenly visible to predators. Within the population of peppered moths, the darker forms then had the selective advantage. Over 50 years, they became the dominant type.
- However, later environmental legislation reduced air pollution in the area, and the trees started to return to their natural colors. Now the selection advantage flipped in favor of the lighter speckled moths. Although this example does not demonstrate evolution of a new species, it does show how natural selection can rapidly change the favored genes in any population.

The Unconformity Feature

- Under the punctuated equilibrium model, transitional forms are difficult to find. The evolution of new species would occur, but very rapidly. As we know, the geological record is full of gaps; thus, it is likely that we might miss some of these sudden changes.
- Consider the unconformity feature, which is a break in the sedimentary geologic record. An example is an unconformity in the United Kingdom. The yellow rocks on the top of this exposure are called Inferior Oolite; they are marine rocks. They were deposited in the Middle Jurassic, about 170 million years ago. The rocks below

are gray carboniferous limestone and probably date to around 350 million years ago.

- The sediment below was at one time transformed into a rock and then tilted. Those tilted rocks were uplifted and exposed and eroded to an irregular surface. When sea levels rose, the ocean returned, and the upper layer was deposited.
- The eroded area created the unconformity between the two rock units. The unconformity in this case represents a potential gap—missing information, or lack of strata—of about 180 million years.

Evolutionary Transitional Fossils

- In general, the scientific community leans toward punctuated equilibrium. It is accepted that gradualism does occur in some species—certain microfossils, for example. And with punctuated equilibrium, we still find transitional models.
- One of the most significant examples of a transitional model—and perhaps the most famous fossil of all time—was *Archaeopteryx*. *Archaeopteryx* was a bird—but one that possessed a bony tail and a beak full of teeth. It also had odd reptile claws in the center of its wings. This creature represents a wonderful transition between a ground-dwelling reptile and a bird similar to the birds we know today.

Appearance of the First Land Vertebrate

- Our objective here is a holy grail of the transitional form: a fossil that demonstrates one of the most important moves that vertebrates would make—from the water onto the land. What we’re looking for is a group of creatures called tetrapods.
- Humans are tetrapods. Tetrapods are animals that have—or, in the case of whales and dolphins, had—four limbs. The classic structure of a tetrapod is this: a pelvis attached to a backbone, a spine with a series of interlocking spurs, a curved rib cage to support and protect the internal organs, nostrils for breathing, and limbs that follow a

specific pattern—from one bone to two bones and then to five digits at the end.

- The hypothesis is that the first land vertebrate would look a bit like a fish that has some of the features of a tetrapod. Some paleontologists refer to this as the elusive fishapod.

Ancestor of the Tetrapod

- Fish went through radiation and diversification in the Devonian, producing the bony fish. It is in this category that we will most likely find the fish that became a tetrapod. Scientists believe this fish is from the lobe-finned fish group. Slow swimming, these fish beat their lobe-like fins from the sides of their bodies. The fins were joined to the fish by one bone.
- Within the lobe-finned fish is a group called the Rhipidistia, including *Eusthenopteron*. This was a Late Devonian fish, from about 385 million years ago. It is of particular interest because it possesses a pattern of bones very similar to the later tetrapods.
- Eusthenopteron* had a humerus, an ulna, and a radius in the pectoral fins; it had a femur, a tibia, and a fibula in the pelvic fins—mirroring the pattern in our four limbs. A fish similar to this probably gave rise to all the tetrapods.



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Tetrapods share several skeletal features: a pelvis attached to a backbone, a curved rib cage, and limbs with bones in the pattern of one to two to many.

Ichthyostega

- With the paleontologists still in search of the elusive fishapod, in 1930, a strange four-legged fossil called *Ichthyostega* was found. It was discovered in Greenland by a Swedish paleontologist, Erik Jarvik, an expert on *Eusthenopteron*. As predicted, *Ichthyostega* was a fish on legs. It had a fishlike body, and at the end of its legs were feet with five toes.
- This creature was clearly adapted to walk on land. It was also quite large—about 5 feet long from its nose to the tip of its tail. *Ichthyostega* was a true amphibian; it was happy in water, but it was also able and mobile on land.
- There was a bit of disquiet in the scientific community after this discovery, however. *Ichthyostega* did not look very transition-like. In the reconstructions by Jarvik, it looked far too much like a fully developed tetrapod.

Acanthostega

- This general disquiet led Jenny Clack of Cambridge University to mount a new expedition to Greenland in 1987. In addition to *Ichthyostega*, she found an additional Devonian tetrapod that she named *Acanthostega*. *Acanthostega*, about 2 feet long, was smaller than *Ichthyostega* and did not look much like what was expected of a tetrapod. That was quite a surprise.
- For example, *Acanthostega* did not have five toes; it had eight. This was an important find because it shatters a basic assumption of what tetrapods were. It appeared that early on, the number of digits in the fingers and toes of these creatures was variable.
- Also, its limbs jutted out of the side of the body. That does not make sense for a land-dwelling creature. For an animal to walk on the land, its limbs must be positioned underneath.
- Acanthostega* did not have any wrists or ankles—another feature needed for locomotion on the land. Its hips didn't support much

weight. *Acanthostega*'s feet apparently weren't feet at all; they were paddles.

Evolution of Limbs

- At first, scientists speculated that limbs evolved to drag fish out of shrinking ponds in a hot Devonian desert environment. Natural selection would favor the fish with strong limb-like fins. Another speculation was that just as jaws were not originally developed to bite—but, rather, to improve respiration—perhaps limbs didn't evolve to walk. If that is the case, the question is: Why did limbs evolve at all?
- The answer is found in a reinterpretation of the Devonian ecosystem. The Devonian ecosystem was not all hot, arid, sterile desert. It was also wet and contained a vast proliferation of flora. In fact, by the end of the Devonian, we start to see the first forests.
- A new ecosystem was emerging—a swampy, plant-tangled environment close to the river's edge. This new environment was rich in organic debris and plants—an ideal environment for exploitation. There were invertebrates and small fish that would attract predators, such as *Acanthostega* and *Ichthyostega*. This was also a good environment for a small tetrapod, which would have made a nice snack for the fierce predators that patrolled the open waters.
- The current view of scientists is that limbs and digits didn't evolve to help tetrapods stride purposefully across the land; they evolved to help the mostly aquatic tetrapods navigate their way through swampy, plant-tangled environments. It makes more sense to have very flexible limbs—rather than fins—to move around in this environment.
- But we are still missing something in this story. We have not found the elusive fishapod. In the next lecture, we'll hear the story of how the evidence of the fishapod came to light.

Suggested Reading

Gould, ed., *The Book of Life*.

Laurin, *How Vertebrates Left the Water*.

Questions to Consider

1. Given the success of the vertebrates once they developed a mineralized skeleton and jaws, could we regard the group as being superior to the arthropods?
2. Why do you think transitional forms generate so much attention from the scientific and religious communities?

Tiktaalik—The Search for a Fishapod

Lecture 22

At this point in our story, we have discovered early tetrapods and lobe-finned fish, but we have no convincing transitional form to link the two together. In this lecture, we'll continue our quest for the elusive fishapod. We'll also expand our story by considering what are called living fossils, by introducing the paleontological superstar *Tiktaalik*, and by looking ahead to new finds and possibilities in the story of tetrapod evolution.

What Is a Living Fossil?

- A living fossil is a species that has been in existence for a long time but has evolved very little. The brachiopod *Lingula* is an example of a living fossil. *Lingula* is an inarticulate brachiopod, which means it cannot open its shell and gape, as articulate brachiopods do.
- *Lingula* is definitely a survivor. The family of brachiopods to which *Lingula* belongs has remained relatively unchanged since the dawn of the Cambrian. It was one of the few creatures to prosper through one of Earth's greatest crises—an extinction event 250 million years ago.
- Another type of living fossil is from the Lazarus taxon, named in honor of Lazarus, whom Jesus brought back from the dead. Creatures rediscovered as living forms that were previously thought of as extinct are called Lazarus taxa.
 - An example is the *Metasequoia*, or dawn redwood. About 50 million years ago, it was part of extensive forests that spread as far as northern Canada.
 - It was considered extinct, a fossil, until 1941, when it was discovered in a canyon in the Sichuan-Hubei region of China. An extensive breeding program followed, and now, *Metasequoia* has become widespread again.

The Coelacanth

- One of the Lazarus taxa—the renowned lobe-finned fish called the coelacanth—played an important role in our understanding of the origins of tetrapods. Coelacanths first appeared during the Devonian period, but they were largely gone from the fossil record by the end of the Cretaceous. It's thought that these fossils had suffered in the same extinction event that eradicated the dinosaurs.
- Coelacanth fossils, however, were identified as extremely important in the tetrapod story. The coelacanth had a fleshier fin, which could be a precursor to true tetrapod limbs. Imagine the interest that was generated when a modern coelacanth was discovered by Marjorie Courtenay-Latimer in South Africa.
- James Smith, of Rhodes University, eventually identified the fish as being a coelacanth, a creature that was considered extinct since the disappearance of the dinosaurs 65 million years ago. Smith predicted that the fish probably used its fleshy fins to walk on the ocean bottom; the coelacanth was preadapted for walking on land. The coelacanth, even back in the 1920s, became an international sensation.
- Years later, a live coelacanth was found. Unfortunately for the hypothesis, though, it showed no evidence of walking on the ocean floor. This coelacanth swam; it was clearly a fish. It is thought that only coelacanths in shallow waters went extinct at the end of the Cretaceous; the deepwater forms continued to exist.
- At this point in the story, we still have no convincing transitional form to link tetrapods and lobe-finned fish together. This is where our narrative turns to more recent times.

Red Hill

- In the early 1990s, Neil Shubin of the University of Chicago was investigating a particular group of sediments called the Devonian Catskill Formation. These were mostly terrestrial deposits that spanned about 20 million years of the Upper Devonian period. A significant exposure of the Catskill rocks is called Red Hill.

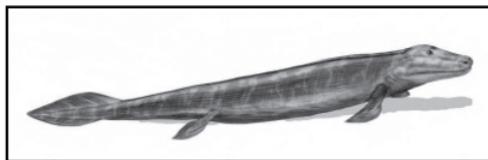
- Red Hill was deposited on Euramerica, which was formed by the collision of Laurentia, Baltica, and the continental fragment Avalonia. The collision began in the Middle Devonian and continued into the Early Carboniferous. This mountain-building event in North America was called the Acadian orogeny.
- As the Acadian orogeny progressed, rivers and streams carried sediments eroded from the rising Acadian mountains. These rivers moved out across a broad coastal plain and eventually dumped their sediment in a series of deltas in the Catskill Sea. It was within these delta complexes that the rocks in Red Hill were originally deposited as sediments.
- The sediments at Red Hill are generally red, reflecting the hot, oxidizing climate under which they were deposited. The deposit also has thin green strips of sediment; most likely, these were ponds and pools that lay on top of the delta between the meandering river channels. The green color arose as the organic material around the edges fell into the ponds, rapidly using up all the oxygen in the water. The green color represents minerals in a semi-reducing environment.
- Shubin, who was particularly interested in tetrapods, collected fossils from this spectacular section. He found *Hyperpeton bassetti*, a creature that lived in the shallow margins of the river channels and ponds. It was a tetrapod, but it was not a fishapod—the transitional form.

Ellesmere Island

- Shubin realized that he would have to search elsewhere to find the elusive fishapod. Given that deltaic environments were reliable places to find early tetrapods, Shubin looked for similar environments but in older rocks. Logically, the missing link should be somewhere between the emergence of lobe-finned fish, 390 million years ago, and the deposition of the Red Hill rocks.
- Shubin mounted an expedition to Ellesmere Island in Nunavut, Canada. During the Devonian, this area was not at its current cold

location at 78 degrees north; it was very close to the equator. Rocks here belonged to a group of rocks called the Fram Formation, from the Middle Devonian, deposited by rivers and streams.

- After an initial unsuccessful search in 1999, in 2000, Shubin's team hit the right strata. Both the sediments and fossils in some strata indicated freshwater conditions. A third quarry was opened up, and in 2004, a member of the team found an odd-looking fish. In fact, it was paleontological gold. The fish, 375 million years old, was about 3 to 6 feet long and exhibited an unusual mix of features—some of which were fishlike, such as fins and scales, and a primitive fishlike jaw.
- The fossil had some non-fishlike features, as well. It had a flat head like a crocodile. It did not have a fused head and shoulder, like other fish; it had a neck. Also, its bones in the limbs, or fins, conformed to the tetrapod arrangement of limbs: one to two to many. There was a suggestion of a wrist joint, allowing this fish to do a kind of push-up on the floor of the water body. The webbing on its fins and elbow joint was also much reduced, allowing its limb-fin flexibility and range of motion.



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Tiktaalik was 3 to 6 feet long and exhibited both fishlike features, such as fins and scales, and some non-fishlike features; the flexibility of its fins likely made it an able swimmer.

Tiktaalik

- The elders of Ellesmere Island suggested that Shubin name the fossil *Tiktaalik*, referring to a large freshwater fish in Inuktitut.
- *Tiktaalik* probably lived close to margins of water, spending its days just partly submerged. It probably ate smaller fish and invertebrates. It's possible that its push-up ability allowed it to lift itself suddenly out of the water and perhaps snap at a passing arthropod—like a crocodile in many ways.

- *Tiktaalik*, like the coelacanth before it, was an international star. It appeared in newspapers and magazines and on television. *Tiktaalik* was heralded as a true transitional form, an authentic missing link between the fish and the tetrapods. The holy grail of transitional forms had been found.

Beyond *Tiktaalik*

- In January 2010, in the journal *Nature*, a paper was published that would potentially throw open the study of tetrapod evolution all over again.
- The paper recorded a spectacular find made in the Zachełmie Quarry, in the Holy Cross Mountains in Poland: trackways made by some sort of unknown creature. These trackways indicated that the creature probably had four limbs. That creature may have been walking; it may have been a tetrapod. On the trackways was evidence of toes on the ends of feet.
- Per Ahlberg, at the University of Uppsala in Sweden, speculated that the creature walked like a salamander with a kind of a swinging gait. It was not the salamander we know today, however; this salamander was 8 feet long. But there's also something else quite surprising about this find. It comes from the Middle Devonian, about 395 million years ago, predating *Tiktaalik*.
- If this is truly evidence of an animal walking across the land, it means that even before *Tiktaalik* came into being, tetrapods were in existence. This find pushes the timing of the evolution of tetrapods farther back into time. It also changes our understanding of the environment in which tetrapods evolved.
- *Tiktaalik* and its kin evolved in deltaic, swampy, freshwater environments. The Zachełmie Quarry does not record such an environment: It is a marine environment. Poland, at this time, was in the tropics. The environment would have been an intertidal mudflat baking in the hot Sun. The tides in these environments washed up

and concentrated dead fish and organic debris—setting a rich dining table for anything that could get out of the water.

New Finds and Possibilities

- Today is an extraordinary time to be a paleontologist. We’re finding new and exciting exposures of rocks containing fossils. At one time, many of these areas would have been almost impossible to reach, but now, they are available to paleontologists.
- Because we can now access these remote areas, the story of the tetrapod will develop even further. We’ll fill in more of the gaps, and the continuing story will challenge our perception of the evolution of many vertebrates.
- In the next lecture, we’ll proceed to a world where our ancestors were living quite happily—purposefully striding across the land. We’ll visit the period called the Carboniferous.

Suggested Reading

Amos, “Fossil Tracks Record ‘Oldest Land-Walkers.’”

Shubin, *Your Inner Fish*.

Questions to Consider

1. With the expansion of the human race across the planet, what is the likelihood of the discovery of new Lazarus taxa?
2. If *Tiktaalik* proves to be predated by an earlier tetrapod, what happens to its status as a transitional form?

Carboniferous Giants and Coal

Lecture 23

Coal powered the Industrial Revolution—first in England, and then in the rest of the world. A phenomenon that changed the world, the Industrial Revolution saw the invention of the steam engine and other technologies, economic expansion, the rise of new cities, and mass migration from the countryside into those cities. Coal mostly formed 359 to 299 million years ago. In fact, the period in which coal formed gets its name from coal: the Carboniferous period. In this lecture, we'll investigate the Carboniferous world and learn how and why it produced so much coal.

Mississippian and Pennsylvanian Periods

- On some lumps of coal are visible faint imprints that look like leaves, ferns, or stems of some sort. These are, in fact, fossils of plants that lived many millions of years ago. They are the products of a hot, steamy, swampy environment.
- There are extensive Carboniferous coal deposits in many places around the world, including in North America. In North America, the Carboniferous is split into two subperiods. The Mississippian, 359 to 318 million years ago, produced more limestone than coal, and the Pennsylvanian, 318 to 299 million years ago, produced vast amounts of coal.

Types of Coal

- Coal forms when plant material falls into a body of water that has low oxygen concentrations. The organics then start to accumulate, and while some of the organics are oxidized by oxygen in the water, that oxygen is rapidly used up.
- This is the ideal environment in which peat starts to accumulate; that's the first stage in coal formation. As the peat is buried by sediment and heat and pressure drive off its volatiles, eventually,



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A typical analog for the environment in which coal forms would be the swamps of the Mississippi.

the peat is transformed into coal. There are several grades of coal, ranked by how much heat and pressure produced them.

- Lignite is a brown coal used for electricity generation. It's around 60 to 75 percent carbon content.
- Subbituminous coal has various uses, including as a source of hydrocarbons for the chemical industry.
- Bituminous coal has various applications, including the production of coke, which is used in smelting iron ore.
- Anthracite, with more than 91.5 percent carbon, is the highest rank of coal. Because of the intense heat and pressure that have gone into its production, it's regarded by some as more of a metamorphic than a sedimentary rock.

- The value of coal has been known for a long time. It was used by the ancient Greeks, by some Bronze Age Britons, and by the Romans. About 984 billion short tons of coal reserves exist globally today.

Cyclothsems

- Geologically speaking, coal is found in sedimentary packages called cyclothsems, which represent the repeated rise and fall of sea levels. The layers include sediments indicative of river delta, as well as marine deposits.
- The marine sediments represent the period of highest sea level. As sea levels fell, previous marine sediments were exposed to the atmosphere, and they developed an erosion surface. That surface was then covered as rivers started to migrate across this area; when swamp conditions returned, coal was ultimately formed.
- Eventually, sea levels rose again, flooding started, and the cycle was repeated once more. Cyclothsems are sometimes found stacked in vast numbers, as many as 40 to 50 at a time. In some cases, 100 cyclothsems have been recorded, representing the repeated rise and fall of sea levels.
- In North America, some coal units can be traced for thousands of square miles, indicating the vast extent of the swampy, deltaic coal-forming environment of the Carboniferous.

Sea Levels Rise and Fall

- It is speculated that the cycles of sea-level rise and fall were caused by local vertical faults in the crust or the pressures of large accumulations of sediments. These localized effects, however, cannot account for the vast extent of some of the cyclothsems recorded in coal deposits. Many of them can be correlated over vast distances.
- The cyclothsems most likely imply a global change in sea level. A crucial question is: What was controlling the depth of the oceans globally during the Carboniferous? The answer is the repeated

advances and retreats of what is now known as the Permo-Carboniferous glaciation.

- As glaciers formed, water was locked in glacial ice. Because there was a net loss of water return to those oceanic areas, sea levels dropped. When that occurred, the lowland swamps emerged and rivers moved across the newly exposed land.
- During an interglacial period—a period when the ice melted and returned water to the oceans and rain stayed on the land—the sea levels rose. Then, coal production stopped. There was a return to the marine part of the cyclothem.

Carboniferous Swamps

- Carboniferous swamps were vast—continentally vast. The plant ecosystem within these swamps continued to evolve vertically upward, even more so than in the Devonian forest. The plants occupying these Carboniferous swamp environments were spectacular but strange.
- The most spectacular were the ancient club mosses. The club mosses today, like their earlier Devonian ancestors, are very small. But in the Carboniferous, it was a different story.
- An example was *Lepidodendron*, a club moss over 100 feet tall. It had fronds on the tops of large trunks and looked like a palm tree. It also had distinctive leaf scars on the trunk, creating a characteristic diamond pattern. These are some of the most common fossils found in coal deposits.

Amphibians of the Carboniferous

- The tetrapods had evolved from the Devonian into the Carboniferous; the Carboniferous had an entire suite of amphibians that were much more diverse than the amphibians found in today's ecosystem.
- Today's amphibians are fairly diminutive creatures. A salamander in the Carboniferous and Permian, however, was as large as a

crocodile. Other amphibians became the amphibian equivalent of water snakes. For example, *Ophiderpeton* was about 28 inches long and had 230 vertebrae in its backbone.

- Others, such as *Seymouria*, were well adapted to living on land. *Seymouria* had powerful, muscular legs, and it adapted a tough, dry skin to help reduce water loss while crossing the land surface.

Reptiles of the Carboniferous

- In addition to the amphibian, another small tetrapod evolved in the Carboniferous. Its ancestors would ultimately come to dominate the planet much later in Earth's history. These are the reptiles.
- The early reptiles were somewhat humble creatures. For example, *Hylonomus* was small, about 8 inches long, and looked very much like a lizard. It was probably one of the earliest fossil reptiles, dating from about 312 million years ago. This creature had a flexible neck and a lightly built skeleton. It had hands and feet with long digits and very sharp teeth. *Hylonomus* was most likely an early insectivore, as were many of the early reptiles.
- The greatest innovation of the reptiles was their ability to break ties to the water. Amphibians, however large and impressive, still had to return to the water to spawn. The reptiles' major adaptation was the amniotic egg: a water-impermeable membrane surrounding a fluid-filled cavity. The shell itself had tiny pores to permit waste gases to diffuse out and oxygen to diffuse into the developing embryo.
- Another great advantage to egg laying was that eggs can be buried. As the embryo passed through the vulnerable tadpole stage, it would not be visible or susceptible to predators.

Arthropods of the Carboniferous

- The Carboniferous saw the emergence of the first true spiders, the Mesothelae. Like modern spiders, they had the ability to produce silk.

- Another interesting arthropod is *Arthropleura*, a millipede-like creature—but a millipede more than 8 feet in length. This giant arthropod apparently was a fairly familiar sight; its tracks are common. *Arthropleura* was probably an herbivore; scientists have found fossils that contain plant spores in its gut, and its coprolite (fossilized excrement) also contains fossil plant spores.
- Giant arthropods were not only found on the ground. *Meganeura* was a giant dragonfly-like insect with a wingspan of around 30 inches. It probably fed on other insects in the environment, as well as smaller tetrapods.

Higher Oxygen Levels

- Why did insects in the Carboniferous grow so large compared to insects today? It's possible that today, they've just been outcompeted by larger tetrapods. However, in the past, there was most likely a more fundamental physiological reason for their size.
- Insects take in oxygen through holes in their bodies called spiracles. These spiracles connect to a series of branching tubes called the tracheal system, and it's through these that oxygen diffuses. It's an effective system for getting oxygen around a body—but only for fairly small creatures.
- To get larger, an insect needs to use more tubules. Eventually, it would reach a point where the creature would be mostly tubule and not much else. This, we think, today places an upper limit on how large insects can grow.
- The key factor that allowed the giant insects and arthropods of the Carboniferous was oxygen. During the Carboniferous, there were vast amounts of carbon being removed by peat formation. The continents were turning green, and all those plants were producing a great deal of oxygen via photosynthesis. Thus, oxygen levels in the Carboniferous atmosphere started to build and build.

- Oxygen levels, we think, rose to about 35 percent in the Carboniferous (they are only 21 percent today). This higher concentration of oxygen permitted oxygen to diffuse more easily through a creature, which probably meant that their tubules could be thinner. As a consequence, these insects—these arthropods—could grow very large.
- Another consequence of the high oxygen levels, however, was that the Earth was turned into a tinderbox. Fires sparked by lightning were probably common. Fusain, which is a dark, dusty deposit on coal, could be the possible remnant of some of those ancient forest fires.

Evolution Flourishes

- The Carboniferous was a remarkable period—one vitally important to the development of the modern Western world. Not just coal and tetrapods developed in this period, however. For example, the Carboniferous saw the radiation of new plants and plant ecosystems associated with the increase in diversity of fungi. All modern classes of fungi had evolved by the Late Carboniferous.
- In the oceans, fish continued to diversify, and bony fish continued to evolve. The Carboniferous was also an important period of the radiation of the sharks. What's more, this period saw the creation of extensive Carboniferous coral reef systems composed of rugose and tabulate corals and beautiful meadows of crinoids.
- In the next lecture, we'll look at some small lizards of the Carboniferous and see what they would become in the next geological period, the Permian.

Suggested Reading

Beerling, *The Emerald Planet*.

Lane, *Oxygen: The Molecule That Made the World*.

Questions to Consider

1. Could Carboniferous coal be thought of not only as fossilized plant remains but also as fossil sunlight that fell on the Carboniferous swamps and was transformed into plant tissues?
2. If the oxygen levels experienced during the Carboniferous had been maintained, is it possible that the vertebrates would not have been assured their position as the dominant animals on land?

Amniotes—The Shape of Things to Come

Lecture 24

This lecture begins by explaining how scientists classify life. The classification system was created in the 18th century by Carl Linnaeus. Linnaeus gave creatures a two-part name—a Latin noun, called the genus, followed by a specific adjective, called the species. This is the basis of the binomen system. The lecture also explores the three groups of amniotes that evolved: anapsids, diapsids, and synapsids. The synapsids are especially interesting because this group of amniotes ultimately gave rise to the mammals.

From Eukaryota to *Homo Sapiens*

- The Linnaean classification system is based on a logical hierarchical scheme. Consider humans in this hierarchy. At the very broadest level, we are members of the superkingdom Eukaryota. The eukaryotes are creatures that contain a specific nucleus where the genetic material sits; they have organelles in the cytoplasm. Basically, the superkingdom Eukaryota includes everything that is more complex than the archaea or the bacteria.
- Under Eukaryota, humans are in the kingdom Animalia—which includes all animals, from a worm to an elephant. Within Animalia, humans are members of the phylum Chordata, which includes anything with a notochord. Our subphylum is Vertebrata—all creatures within the chordates with a backbone. Our class is Mammalia—creatures with very specific features, such as the ability to lactate and the state of being warm-blooded. Our order is Primata, which we share with baboons, lemurs, and chimpanzees.
- Getting closer to home, our family is Hominidae—including such creatures as *Australopithecus* and *Zinjanthropus*. Our genus is *Homo*—a grouping that includes Neanderthals and us: *Homo sapiens*.

Classifying Life

- Using the Linnaean system, our genus, *Homo* (a generic Latin noun), is followed by a specific adjective naming the species, *sapiens*. In classifying, the generic name can be followed by many different species names for different genera—for example, *Homo erectus* and *Homo habilis*.
- The names chosen to describe species come from a variety of sources. Scientists can decide to honor a person; an area, often where the specimen was collected; or perhaps, describe some feature of the species that particularly designates its form. All these forms are then Latinized.
- For example, *Ancyrochitina narcissa* was named because the top of the creature resembles a narcissus; *Ancyrochitina gogginsensis* was collected from Goggin Road; and *Angochitina milleri* honors a micropaleontologist, Giles Miller, who helped collect the material that ultimately yielded this species.
- The various codes and regulations outlining the definition of new species and groupings of species are controlled by a number of international bodies, including the International Code of Botanical Nomenclature and the International Code of Zoological Nomenclature.

Taxonomy

- Organizing life in these logical hierarchical schemes is called taxonomy. The Linnaean system is useful, but it can fall short at times. Consider the class Pisces, which includes fish, such as the cod and lungfish. Our first instinct is to classify these fish together: They both live in the water; they both have fins. However, there's a problem. On a basic biological level, the lungfish is actually more closely related to the frog than to the cod.
- Today, taxonomy is leaning toward a system called cladistics. Cladistics groups creatures on the basis of shared characteristics, not on how each individual creature looks superficially. For

example, no one today would classify a dolphin as a fish, even though both might look similar.

- In cladistics, the relationships between animals are presented on a cladogram, or an evolutionary tree of life. The ancestor of all the species is at the bottom of the diagram, and the descendants of that original creature branch at various points to form new species.
- Any grouping of organisms must, under cladistics, contain all its descendants. Valid groupings include all descendants; such groupings are called monophyletic. Groupings that are not valid do not contain all the descendants; these groupings are called paraphyletic.
- Interestingly, under cladistics, there is no such thing as a reptile. Reptiles are a group that does not contain all descendants, including the birds and the mammals. Therefore, the grouping reptile is paraphyletic and not valid. Reptiles are included in a wider group called the amniotes—that is, all the tetrapods that have a terrestrially adapted egg.

Amniotes

- The ancestor of the amniotes is a primitive lizard, *Hylonomus*. From this reptile, three groups of amniotes would evolve: anapsids, diapsids, and synapsids. These broad groupings of amniotes are most easily differentiated by the presence and number of holes in the skull behind the eye socket. Those gaps, or holes, are called fenestrae, meaning “windows.”
- The anapsids are the most primitive members of the group. They have a complete skull, with no gaps. *Hylonomus* belongs to this group, which places it at the base of the evolutionary tree.
- The diapsids have two fenestrae in their skulls, one directly behind the eye socket and one just slightly above. Diapsids are an extremely successful group of amniotes. They include the lizards, crocodiles, birds, and—everybody’s favorite monster—the dinosaurs.

- The synapsids are especially interesting because this group of amniotes ultimately gave rise to the mammals. The synapsids have just one fenestra, behind the eye socket. The synapsids dominated the Permian, 299 to 251 million years ago.

Synapsids

- One of the most famous Early Permian fossil localities is the Texas Red Beds. These include a fascinating mix of tetrapods and some spectacular synapsid reptiles, a group called the pelycosaurs.
- A top predator of that environment was the pelycosaur *Dimetrodon*. *Dimetrodon* was not a dinosaur, however. The dinosaur did not evolve for many millions of years after *Dimetrodon* had become extinct. *Dimetrodon* was about 13 feet long and had a large jaw with a set of slashing teeth. Perhaps its most prominent feature was its sail, which probably aided in thermoregulation. Because these were likely cold-blooded creatures, they would have to rely on the external environment to either cool them or heat them.
- Another pelycosaur in the Texas Red Beds was *Edaphosaurus*, a herbivore of more than 600 pounds—probably one of the earliest herbivorous vertebrates on the scene. Why did we have to wait more than 50 million years for the herbivorous vertebrates to appear?
 - Because most plant material contains a great deal of cellulose, it's very difficult to digest. Cows have solved this problem by recruiting the aid of fermenting bacteria in the gut. These fermenting bacteria, however, require fairly stable temperature environments. The cow accomplishes thermoregulation through its sophisticated mammalian metabolism.
 - A cold-blooded creature, however, lacks such a sophisticated mechanism. But another way of maintaining a fairly warm inner core of the body is to get big. Thus, it was likely that herbivory in vertebrates at this early stage had to wait until the creatures got sufficiently large.



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Many therapsid specimens are found in the South African karoo.

- Pelycosaurs are sometimes called mammal-like reptiles. True mammals would not evolve for a long time, but eventually, they would evolve from relatives of the pelycosaurs, later in the Triassic, about 200 million years ago.

Therapsids

- In the Late Permian reptile world, pelycosaurs were relatively restricted to tropical regions, but a new group of synapsids would evolve from them: the therapsids. The therapsids started to explore the massive supercontinent called Pangaea.
- Therapsids adapted a variety of shapes, sizes, and lifestyles. They had larger skull openings behind their eye sockets, which may have indicated more muscle mass to operate very powerful jaws. They had powerful canine teeth. In addition, they were probably much more agile than their pelycosaur cousins.

- The most common therapsid was the herbivorous dicynodont, which made up more than 90 percent of therapsid diversity. It was probably the first truly abundant vertebrate herbivore on the surface of the planet.
- Part of the success of the dicynodont was the evolution of a secondary palate, which allowed the creature to chew and breathe at the same time. This is an important feature. The vertebrates that preceded these herbivorous creatures had been meat eaters. Meat contains a great deal of energy; plants, in comparison, contain much less. For a plant eater, it helps to be able to keep eating while breathing, to consume more.
- Dicynodonts had a variety of lifestyles and specializations. Some of them had cropping jaws; some had crunching jaws. These diverse varieties suggest a climate that was reasonably mild and relatively stable, so that it supported a relatively constant food supply.

Gorgonopsians and Archosaurs

- The top predators in the Late Permian were the gorgonopsians, whose name comes from the fearsome creatures in Greek mythology called the gorgons. These were the first real saber-toothed killers on the planet. They had a massive gape, with giant saber-like teeth that would sink into their prey.
- The gorgonopsians were part of a group called the theriodonts—the group of creatures containing mammals, as well. Theriodonts have very mammal-like features, including teeth that are differentiated to perform different functions. They had fully developed temporal fenestrae and rear legs that were more pulled in underneath the body. Also in common with humans, they developed small bones in their ears that allowed them to hear.
- Therapsids lived in conjunction with a particular type of diapsid reptile called the archosaur. Although the archosaurs were a minor component of this particular reptile landscape, these creatures

showed great promise: from the archosaurs came crocodiles, flying pterosaurs, birds, and of course, the dinosaurs.

- In the Permian, land animals exploited new niches, herbivores came into being, and vertebrates took to the skies. The Permian saw the evolution of more modern-looking plant flora, and the oceans were full of rich coral reefs. Remember, though, how the tropical paradise of the Ordovician ended suddenly in ice. The biosphere of the Permian would end, too—but this time with heat. We'll cover that event in the next lecture.

Suggested Reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Foote and Miller, *Principles of Paleontology*.

Gould, ed., *The Book of Life*.

Questions to Consider

1. When humans first gained consciousness, on what basis do you think they might have classified the life around them?
2. If the synapsids had remained the dominant groups of reptiles through the Mesozoic, would mammals have evolved earlier or are we (as mammals) a product of our own marginalization by the diapsids and, in particular, the dinosaurs?

Permian Extinction—Life’s Worst Catastrophe

Lecture 25

Imagine that a vast number of species on the planet Earth—all the wonderful diversity and richness of the biosphere—were suddenly eradicated, in the blink of a geological eye. The world laid waste, with a complete breakdown of all its interrelated systems, actually happened about 251 million years ago at the end of the Permian. It’s called the End-Permian extinction or the Permian–Triassic extinction event. The feedback mechanisms that had maintained Earth’s homeostasis simply failed; in effect, the planet’s environmental health collapsed. This was a key point in the evolution of the Earth, and we’ll spend two lectures studying it.

Extent of the Permian Extinction

- Before the extinction event, the Permian world was a rich biosphere, full of complex, diverse, and bounteous life. But this world was almost completely destroyed, leaving a barren planet behind, a shadow of its former richness. Rocks that cross the Permian–Triassic boundary on land all tell the same story. They reveal a healthy biosphere for most of the Permian and then utter devastation in the last part of the Permian and the early part of the Triassic.
- Trilobites and the eurypterids disappeared, as did the rugose and tabulate corals. In fact, coral reefs would not recover for many millions of years to come. The tropical rain forests vanished. By the end of the Permian, acanthodian fish—extremely important in the Devonian—were gone forever, only to be known by their fossil evidence.
- There were extinctions in every species group; in fact, this is the only time that insects suffered a mass extinction event. Of the vertebrates, more than two-thirds of the tetrapod faunas were lost at the end of the Permian. Many of the therapsid reptiles were gone.



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Snails suffered a 98 percent extinction at the end of the Permian, and clams, 59 percent.

Plant ecosystems were disrupted; the formerly lush flora that had spread across many parts of Pangaea disappeared.

- Geologists used this sudden change in fossils to define the end of the Permian and the start of the next period. But this event also defines the end of the entire Paleozoic era. It marks the close of a whole group of periods, a whole characteristic play of fossils—the conclusion of 251 million years of Earth's history.

Evidence of the Extinction

- Evidence of the complete and utter collapse of the biosphere is found in Earth's other systems. Because the Earth's systems are interrelated, changes in one system severely affect other systems. In addition to the loss of species recorded in the fossil record, we find other signals preserved in the rest of the geological record.
- One of those signals was an incredible concentration of fungi spores in terrestrial sediment. Fungi, of course, are decomposers of

the plant material that falls down in forests. Such a high abundance over a period of time could only represent one thing: the destruction of much of the floral biomass in the End-Permian world.

- In addition, coal production suddenly stopped at the end of the Permian. It was replaced by red beds—sediments that indicated hot, arid conditions. This change represents a sudden shift in climate and the death of a major ecosystem.
- Further, the sedimentary depositing mechanism, which formerly consisted of meandering rivers, was suddenly replaced by a different type of river system called a braided stream deposit. Scientists believe that the large, meandering routes of the Permian suddenly failed because all the flora died off and could no longer stabilize the banks of the river channels. Another type of river system arose—creating an anastomosing, chaotic-looking deposition of sediment in rivers. It would appear that at the end of the Permian, plants in the landscape were just being stripped away.
- There is isotopic evidence of the mass extinction, as well. Within the Permian–Triassic boundary sediments is a negative carbon-13 anomaly. This indicates that an environment has become suddenly flooded with carbon-12—suggesting the sudden cessation of photosynthesis and the death of creatures composed of carbon-12 organic molecules, with the sudden release of significant amounts of carbon-12 back into the environment.

The Story in the Sediments

- In addition to the carbon-13 anomaly, we find remarkable exposures of deep-sea sediments that were deposited in the Panthalassic Ocean. The sediments, called cherts, have been moved by thrust faults; we find some of these in Japan.
- Cherts are fine-grained, siliceous sedimentary rocks produced by the accumulation of the skeletons of particular tiny microfossils called radiolarians. These are amoeboid protozoans that secrete a silica skeleton around themselves.

- There are many other important microfossils, such as coccolithophores and the Foraminifera, but these are composed of calcium carbonate. Calcium carbonate is more soluble in water at low temperatures and high pressures. As a result, the most remote and deepest part of the oceans are generally free of these carbonate sediments.
- Silica, however, can still be deposited at these low temperatures and high pressures, and microplankton, such as radiolarians and diatoms, formed silica-rich sediments called siliceous oozes. The radiolarian siliceous oozes in Japan record a rather disturbing sequence of events in the world's oceans.
 - Initially, things appeared fine. The rocks are red, showing that iron has been oxidized to the mineral hematite. This indicates that the oceans were healthy; they were well ventilated, with oxygen even in these deep, remote areas.
 - But then the sediments record a change: They turn gray. A greater amount of organic content accounted for the grayish color—meaning that there is less oxygen, because oxygen would oxidize the organic sediments away. The carbon apparently was being preserved.
 - Finally, the sediments turn black, indicating a high organic content. That black color demonstrates that there were oxygen-free conditions at the bottom of the oceans. The deep oceans, at this time, were suffocating. This was not just a localized event, however; it appeared to be a global phenomenon. At the end of the Permian, it would seem, much of the ocean simply died.

An Impact from Space?

- Some scientists, called gradualists, have suggested that the Permian extinction actually represents a very long period, perhaps as much as 10 million years. However, a period of 10 million years does not define a mass extinction event. Others, the catastrophists, believe that the event occurred suddenly—overnight, or perhaps within a day or several years.

- Scientists have asked whether a colossal impact from space could explain the sudden mass extinction event in the Permian. Recent impacts may shed some light on this. For example, in 1908, a great fireball was seen in central Siberia, followed by a detonation and a huge pressure wave. Because the event caused light skies as far away as London, scientists believe dust from the massive explosion had been thrown up into the atmosphere and reflected the sunlight back down to Earth.
- Nineteen years after this event, Leonid Kulik, the chief curator of meteorites at a St. Petersburg museum, mounted an expedition to the epicenter. He was looking for a meteor, but he could not find an impact crater. Instead, he found a wasteland where the trees were flattened, covering an area of about 800 square miles.
- Given this evidence, scientists speculate that perhaps the answer to the Permian extinction was not an impact at all but a massive gas explosion. The current favored hypothesis, however, is that a comet or a meteorite exploded in midair, about 3 to 6 miles above the surface, creating a massive airburst.
- Subsequent investigations have found microscopic silicate and silicate spheres in the soils and the tree resins in the area. They have a high nickel-to-iron signature, common to extraterrestrial sources. Also, iridium, quite commonly associated with extraterrestrial impacts, has been found in some of the peat bogs in the area, and the layers in which it was found date to 1908.

Structures Supporting the Theory

- If the answer to the Permian–Triassic extinction event is an impact from space, the crater would have to be exceptionally large—bigger than Mount Everest, probably hundreds of miles across. There are some interesting structures that may support the theory.
- For example, 155 miles off the northwest coast of Australia is a roughly circular structure about 125 miles in diameter. Called the Bedout High, it may represent the remains of an impact crater

that dates to about the time of the Permian–Triassic extinction. However, its impact breccia has been criticized as being more likely a normal basaltic rock that has been altered by contact with seawater and high temperatures. Also, there is no evidence of ejecta preserved at the site.

- There is some evidence of impact material in Greenland and other areas, but it's very thin—not on the scale of a Permian–Triassic extinction event. The Bedout High, in all likelihood, represents the remains of tectonic rifting—the faults that develop as continents started to drift apart.
- Another possibility was discovered by a joint NASA and German Aerospace Center satellite called GRACE (Gravity Recovery and Climate Experiment). GRACE, which has been taking measurements of Earth's gravity field since 2002, detected the Wilkes Land mass concentration in Antarctica. This is a large gravity anomaly concentrated in a ring-like structure. It's composed, we think, of very dense material—probably mantle material that could have welled up after an impact.
- The Wilkes Land mass concentration is 300 miles in diameter, which would be the equivalent of an impact body that was about 30 miles in diameter. The problem, of course, is that it's under ice and difficult to date. It's thought to have formed at sometime around the Permian–Triassic period, but we have no precise data.
- The mystery of the Permian extinction event would remain just that for a long time. However, the story started to develop in interesting ways in the 1990s; we'll explore that in the next lecture.

Suggested Reading

Benton, *When Life Nearly Died*.

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Hallam, *Catastrophes and Lesser Calamities*.

Questions to Consider

1. In an earlier lecture, we tried to imagine the local environment with 30 percent of the species extinct. Now try that with more than 95 percent.
2. Is it possible that we find it easier to accept mass extinctions like that which occurred at the end of the Permian if we regard the biosphere that went into crisis as somehow “primitive” when compared to our own?

Finding the Killer—The Greenhouse Earth

Lecture 26

The preceding lecture left us with a mystery unsolved: How was the entire biosphere nearly eradicated at the end of the Permian? It has been speculated that a massive impact caused the Permian–Triassic extinction event; however, there is no definitive evidence to support this theory. In this lecture, we'll introduce another potential suspect: Siberian Traps volcanic activity. We'll also look at new information on the extinction event and consider the sequence of phenomena that led to what has been described as the mother of all extinctions.

The Siberian Traps

- The Siberian Traps, near Norilsk in northern Siberia, are flood basalts. *Traps* comes from the Swedish word *trappa*, meaning “stairs.” It refers to the way that flood basalts commonly form a landscape with many stair-like inclinations in the sides of valleys. Flood basalts themselves are outpourings of lava that cover huge areas.
- What is remarkable about the rocks in the Norilsk area, however, is the vast extent of the basalts. In total, they comprise an area about equivalent to Western Europe. Originally, this deposit probably covered 770,000 square miles, with material 0.25 to 1.8 miles deep.
- The vast outpourings of lava were caused by upwellings of hot mantle rocks. As the rocks moved upward, the pressure dropped, which allowed the rocks to melt. When they impacted the bottom of the base of the crust, they generated huge quantities of magma. The exact mechanics of these plumes is still uncertain, but we do know that they're always associated with intense volcanic activity.
- The Siberian Traps erupted along very long fissures, stretching for tens or maybe hundreds of miles at times. They formed huge curtains of lava that moved out across Pangaea.

Increases in Sulfur Dioxide

- For the species living during the Permian, the lava was actually not the greatest problem. Pangaea was a vast supercontinent. If a lava flow started to encroach on an area, animals migrated away. What's more, if lava caused the problem, the question remains: How do we account for all the extinction events in the oceans?
- Another phenomenon must be responsible. Volcanic events of this magnitude cause serious disruption in the biosphere. Volcanic eruptions produce a great deal of gas and dust. The ash in the air can create global dimming, causing global cooling.
- When the sulfur dioxide produced by a volcanic eruption rises into the atmosphere, it is dissolved in rain and eventually forms sulfuric acid. This reflects solar radiation and creates more global cooling. Sulfate aerosols also cause the destruction of ozone; thus, ultraviolet radiation would more readily penetrate to the surface of the planet. All this can severely disrupt photosynthesis, both on the land and in the oceans.



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Ash suspended in the air after a volcanic eruption can severely disrupt photosynthesis, both on land and in the ocean.

Increases in Carbon Dioxide

- Probably the greatest problem for the biosphere created by the Siberian Traps is the carbon dioxide produced from the eruptions. All volcanoes release carbon dioxide, but the Siberian Traps erupted through a particular age of rock: Carboniferous rocks. Carboniferous rocks contain a great deal of carboniferous

limestone—calcium carbonate—and coal deposits, both of which are prodigious sources of carbon dioxide if melted and heated.

- This excess of carbon dioxide most likely caused the intense greenhouse effect recorded at the end of the Permian. In some models, average global temperatures rose by about 8 degrees, contributing significantly to the aridification of the interior of Pangaea. Vast areas turned to desert.
- The upper layers of the oceans warmed. This created a lid of warmth on open bodies of water, which slowed down oceanic circulation. Normally, the ocean basins were kept well ventilated, but in this case, they became starved for oxygen. The biosphere became tremendously stressed, with the land and the oceans both moving into a crisis mode.
- But even this widespread phenomenon cannot explain the massive annihilation during the Permian–Triassic extinction event. We are still missing a significant part of the picture. What we need are new rocks and new information.

The First Phase of Extinction

- The End-Permian extinction mystery remained unsolved for many years, hampered by a lack of strata—geological information—to fill in the gaps. In Jameson Land in Greenland, Paul Wignall from the University of Leeds found some answers. He found rocks that spanned the Permian–Triassic boundary and were rich in fossils, as well.
- These rocks tell us that the extinction started on land. It hit the land flora first and the ecosystem that they supported. At first, this was the effect of global cooling and acid rain that was caused by the Siberian Traps volcanism.
- The acid rain included sulfuric acid from the sulfur dioxide, but there were nitric acids and carbonic acids in the atmosphere as well. These acids caused severe problems for the biosphere. These were

washed out of the atmosphere toward the surface of the planet, with absolutely catastrophic results.

- Plants were killed off by the acid rain and dimming conditions, and soil was washed away to the oceans. The lush forests that produced the coal in Australia disappeared. The plants that supported the meandering rivers and stabilized the banks were gone. The rich diversity of reptiles, amphibians, and insects went into severe crisis. Their ecosystem was being taken away.
- After the acid rain, carbon dioxide remained in the atmosphere and initiated the greenhouse effect. Pangaea, already a fairly dry place, started to become drier. The picture is this: an already devastated plant community with animals struggling, lingering near sources of water that were rapidly dwindling. This phase of the extinction lasted about 40,000 years.

The Second Phase of Extinction

- Next, the extinction moved from the land to the oceans. Why was the first phase of the extinction on land? If the temperature was rising, why didn't the extinction occur in the oceans at the same time? The reason is that oceans are effective temperature regulators.
- In the second phase of the extinction, the wonderfully diverse ocean reef fauna went into severe crisis and was rapidly destroyed. The complete destruction of the reefs took only about 5000 years—about 40,000 years after the extinction event was initiated by the Siberian Traps volcanism.
- Then, the extinction moved back onto the land. The survivors of the first extinction pulse were now hammered for another 35,000 years. The flora was already in ruins. Much of the fauna was gone. If one were to walk across the landscape for the first time since creatures moved out of the oceans, the land would probably be eerily quiet.
- The total length of the Permian–Triassic extinction event was about 80,000 years. Given the evidence in the rock, the event was long and

drawn out; it had not occurred suddenly. This is an important piece of information. An impact event would have caused catastrophic effects that would have been almost instantaneous.

- Remember that we're dealing here with a biosphere that had existed for about 4 billion years; a span of 80,000 years to extinguish nearly all life on the surface of the planet is still a geological blink of an eye.

The Two Excursions

- The new rock sections provided additional isotopic data. There was a negative carbon-13 anomaly associated with the Permian–Triassic extinction event. In fact, there's a negative carbon-13 anomaly associated with all mass extinction events. It seems to be a common thumbprint that something is going dreadfully wrong in the biosphere.
- In the Permian, there were two excursions. The first excursion was related to the first phase of extinction—the end of photosynthesis, with carbon-12 released back into the environment.
- There was a strong second excursion just after the marine extinction event, however—an excursion much greater than would be expected by the continued failure of photosynthesis or the release of carbon-12 from dead organisms. What caused this excursion?

Methane Clathrates

- The answer is found in methane clathrates. Basically, methane clathrates consist of methane trapped in ice. Clathrates are created in permafrost in land environments. They need a cold environment to form, but they can also occur in deeper marine environments along continental margins.
- In the ocean, these clathrates formed by the microbial reduction of carbon dioxide. The microbes lived in the sediments in deep cold-water, high-pressure conditions. They converted various substances, including carbon dioxide, into methane gas.

- As the Earth got progressively warmer, eventually, the deep oceans started to heat up, as well, including those areas along the continental margins. This destabilized the clathrates, which released their methane, with catastrophic results.
- Because this methane was originally produced by bacterial decomposition of organic material in the sediments, it was rich in carbon-12. This explains the large second carbon-13 anomaly following the marine extinction event.
- Methane is about 10 times more effective as a greenhouse gas than carbon dioxide. Temperatures warmed again as a result of the methane, which destabilized more clathrates, which released more methane, which caused more warming. A perfect example of positive feedback.

The Final Phase of Extinction

- The total methane release caused a further temperature increase on land by about another 8 degrees. This led to the third phase of extinction, and the culling moved back onto the land.
- Open water resources became very scarce indeed. Plants retreated further. Animals that had made it through the first wave would go extinct now—80,000 years after the first Siberian Traps eruption.
- Another possible consequence of the release of this methane was that the methane reacted with oxygen in the atmosphere. Atmospheric oxygen levels would fall severely on land, as well as in the oceans.
- What was left after the Permian–Triassic extinction event was a world utterly devastated. A few remaining species would limp over the Permian–Triassic boundary—but into an environment with very few competitors. Survivors would proliferate into the next grouping of periods, the Mesozoic, 251 to 65.5 million years ago, occupying niches that were now vacant.

- The three main reptile types—anapsids, diapsids, and synapsids—survived. One of the diapsids would eventually come to dominate the Mesozoic: the dinosaurs. We'll meet them in the next lecture.

Suggested Reading

Benton, *When Life Nearly Died*.

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Hallam, *Catastrophes and Lesser Calamities*.

Questions to Consider

1. The extinction of more than 95 percent of all species on the planet took place in about 80,000 years at the end of the Permian. Does this strike you as a catastrophic event or a gradual process?
2. It is likely that 200 to 250 million years in the future, the continents will recombine to form another supercontinent. Do you think this will be accompanied by a similar extinction event to that which is associated with the formation of Pangaea?

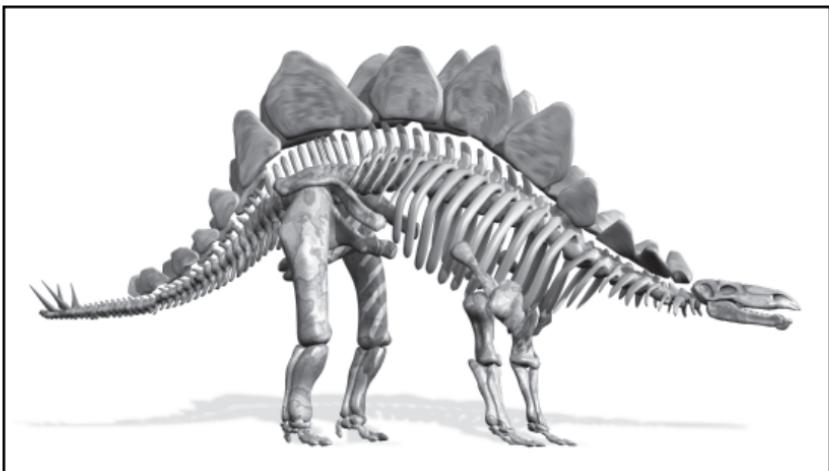
The Dinosaurs Take Over

Lecture 27

This lecture deals with the golden age of dinosaurs: the Late Jurassic. The Late Jurassic was a time of climatic stability. Tropical conditions extended much farther than they do today. The Tethys Ocean was starting to split up the continent of Pangaea from east to west, and a new ocean, the Atlantic, was just starting to form. On land, the forests were filled with conifers, ginkgoes, and giant cycads. And wandering through those forests were possibly some of the most spectacular and awe-inspiring animals that have ever existed. In this lecture, we'll explore where dinosaurs came from, and when, and discuss their extraordinary diversity in the Late Jurassic.

Jurassic Land Creatures

- The largest of the dinosaurs were the sauropods—a classic dinosaur with a long neck and long tail. Sauropods possessed simple, spoon-like teeth, designed to strip away vegetation off branches. Because plant material is low in energy compared to meat, this creature had to feed constantly in order to support its massive bulk.
- One particular species is *Brachiosaurus*, found in an environment of slow-moving rivers, swamps, and lakes. *Brachiosaurus* was a high browser, nibbling on the treetops. It was probably as tall as 30 feet.
- *Diplodocus* was built like a cantilevered bridge and fed on the lower levels, sweeping up vegetation almost like a vacuum cleaner. *Diplodocus* attained lengths of about 90 feet from nose to tail.
- *Stegosaurus* was roughly the size of a school bus, about 30 feet long and 14 feet tall. It was a bizarre-looking dinosaur, with a tiny head held low to the ground and short forelimbs. It had a stiff tail armed with nasty-looking spikes. Perhaps its most recognizable



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Stegosaurus had short forelimbs and a somewhat sprawling gait, which is odd because most dinosaurs had brought their legs fairly well underneath the body.

features, however, were the large plates running down its back. It is speculated that they were used in thermoregulation.

- Where there are giant herbivores, we'll find giant predators. *Tyrannosaurus rex*, however, would not emerge until the Cretaceous period. In the Jurassic, there evolved a creature just as fearsome: the *Allosaurus*. An impressive example of the *Allosaurus* was *Sauropaganax*, which was as large as *Tyrannosaurus rex*—about 4.5 tons and 39 to 48 feet in length.
- The Jurassic biosphere was filled with dinosaurs of all different shapes and sizes, occupying different types of niches. It saw some of the first birds, such as *Archaeopteryx*; turtles; and many different kinds of crocodilian. There were also small mammals and possibly the first representatives of modern-day lizards. It was a truly amazing menagerie of life.

The Jurassic Oceans

- The Jurassic oceans were absolutely brimming with life, having recovered from the End-Permian extinction. They contained many

species of bivalve. The gastropods, which had struggled through the End-Permian extinction, radiated into the Mesozoic and, by the Jurassic, were prolific. The echinoderms had also flourished, and the reefs had recovered. Hexacorals, also called square actinians, developed, and sponge reefs were common. A reef-forming bivalve called *Lithiotis* would create important reef structures during the Jurassic.

- The ocean ecosystem was full of ammonites, belemnites, and cephalopods. And, for the first time, we see modern fish, the teleosts. From these would evolve everything from a salmon to a seahorse. Fantastic marine reptiles, such as ichthyosaurs, roamed the oceans.

Ancestors of the Dinosaurs

- The Jurassic land was clearly dominated by the dinosaurs. Where did they come from and when did they evolve?
- Dinosaurs emerged from the reptile populations that struggled through and survived the Permian–Triassic extinction event. It took about 30 million years or so for complete ecological recovery after that massive annihilation.
- The Early Triassic was still dominated by Pangaea. It saw the beginnings of the Tethys Ocean but certainly no Atlantic. Creatures in this vast landmass migrated freely across the supercontinent. The land was still dry and arid; in fact, warm temperatures probably extended right to the poles. It has been suggested that this was one of the hottest times in recent Earth history (“recent” meaning the Phanerozoic eon, our current one).
- During the Triassic in Pangaea, one of the most common reptiles, the therapsid *Lystrosaurus*, roamed in vast herds. In some deposits, *Lystrosaurus* represents about 95 percent of the fossils.
- Another therapsid, the cynodont *Thrinaxodon*, was especially interesting because it looked a lot like a mammal. It may have been

covered in fur. Also, it had pits in the skull, possibly indicating the presence of whiskers. It had seven neck vertebrae, like modern mammals.

Archosaurs

- The diapsids had diversified into a number of forms, including a group called the archosaurs. The archosaurs were important because they gave us the crocodiles, the pterosaurs, the birds, and of course, the dinosaurs.
- An early archosaur was *Euparkeria*. It is speculated that this was an agile animal, fast-moving, around 24 inches long, and an insectivore. *Euparkeria* also may have been semi-bipedal—the first evidence of a creature on two legs. Although *Euparkeria* was not a direct ancestor of the dinosaurs, it was probably related to the groups of creatures that would eventually evolve into them.

Earliest Dinosaurs

- The earliest known dinosaur fossils are from the Late Triassic, from the Ischigualasto Formation in Argentina. The sediments deposited in this area, originally in a river valley, have revealed a very special fossil. Here, we find one of the first dinosaurs that we can recognize: *Eoraptor*.
- *Eoraptor* was a small bipedal carnivore or omnivore. It was about 3 feet long and probably weighed about 22 pounds. We are still far away from *Brachiosaurus*, *Stegosaurus*, or any of those giants from the Late Jurassic. But there were larger creatures found with *Eoraptor*. *Herrerasaurus*, a fully bipedal carnivore, was 10 to 20 feet long.
- By the end of the Triassic, dinosaurs were present but were just a component of an ecosystem that had a rich variety of tetrapods. They certainly weren't dominating that fauna. How did they become diverse and, ultimately, dominate the Late Jurassic?

Triassic–Jurassic Extinction Event

- Scientists believe that another mass extinction event at the end of the Triassic allowed the dinosaurs to rise to dominance. The Triassic–Jurassic extinction event occurred both on land and in the oceans.
- This extinction event would eliminate the remaining therapsid reptiles that had flourished during the Permian and survived into the Triassic. The dinosaurs, however, would survive in greater numbers.
- Interestingly, the Triassic–Jurassic extinction event was precipitated by the formation of the Atlantic Ocean. It is speculated that a mantle plume developed underneath the supercontinent Pangaea. In addition to creating large outpourings of lava, it started to split the continent. New ocean crust began to form in between these drifting blocks. The ocean broke through, and the Atlantic was born.

CAMP

- Rifting during the Triassic generated considerable volcanism. The lava flow thus created is called the Central Atlantic Magmatic Province (CAMP). Some have suggested that the activity was similar in intensity to the Siberian Traps volcanism that created the End-Permian extinction. The detrimental effects would have been similar. Much sulfur dioxide was produced, but the biggest killer in this event would have been the increased carbon dioxide and the associated greenhouse effect.
- An interesting indicator of the development of a global greenhouse effect at the end of the Triassic comes from fossil leaves.
 - In times of high carbon dioxide, the number of plant stomata (pores used for gas exchange) is low. With lower carbon dioxide levels, plants need greater numbers of stomata because they are trying to maximize the amount of carbon dioxide they take in.

- Fossil leaves found in Greenland and Sweden show a marked decrease in plant stomata, indicating increases in carbon dioxide that match the timing of the CAMP volcanism.
- The temperature at the end of the Triassic was about 5 degrees higher than it is today, but following the CAMP activity, it probably rose by another 5 to 6 degrees. This warming created extinctions on land, with the death of plants and the collapse of higher levels of the food chain—all the creatures that relied on the plant base.

Why Did the Dinosaurs Dominate?

- After the Triassic–Jurassic extinction event, the dinosaurs were no longer just another component of the tetrapod fauna; they dominated it. A number of theories have been put forth to explain this predominance.
- Because they had an upright stance and an advanced metatarsal ankle, dinosaurs were more agile and stable while running. This may have given dinosaurs a greater ability to capture food resources and a competitive edge over their competitors.
- Robert Bakker, a dinosaur paleontologist, has suggested that dinosaurs were endothermic, or warm-blooded, like humans. He believes that they were active and dynamic, and it was this dynamism that gave them the edge.
- But perhaps the dinosaurs were just lucky—which is the theory of Michael Benton of the University of Bristol. He sees no evidence of dinosaurs outcompeting other creatures. He speculates that dinosaurs dominated because they were the first of their kind in the Jurassic—rapidly moving into ecological niches that had been made vacant.

Fragmentation of Pangaea

- Dinosaurs in the Early Jurassic were not as diverse as they would become at their high point in the Late Jurassic. Unfortunately, we have very poor records of the intervening period, the Middle

Jurassic, often referred to as the problematic Middle Jurassic. Obviously, something important happened during the Middle Jurassic, but for a long time, there were few fossils to shed light on what this occurrence might be.

- The best possible explanation is related to the fragmentation of Pangaea. From the Middle to the Late Jurassic, the formerly vast supercontinent experienced an accelerated fragmentation. There were more barriers between areas and less mixing of creatures.
- This theory is confirmed from rare Jurassic sections found in Patagonia. In the Middle Jurassic, Patagonia still allowed easy access between North and South America. Dinosaurs from the two regions were often indistinguishable from one another.
- As time moved on, however, the sediments record that the disparity between the two forms—North American and South American—increased. Because land connections were starting to disappear, the dinosaurs were driven to even more diversity, resulting in the extraordinary dinosaur summer of the Late Jurassic.

Suggested Reading

Fastovsky and Weishampel, *The Evolution and Extinction of the Dinosaurs*.
Martin, *Introduction to the Study of Dinosaurs*.

Questions to Consider

1. In life's story, how much does good biological "design" control which groups of creatures radiate into new niches and how much can be attributed to luck, a case of being in the right place at the right time?
2. Tennyson's view of nature, "red in tooth and claw," is a common manner in which the natural world is presented. Is it this that tends to make people think that the rise to dominance of one group of creatures over another is usually the result of direct aggressive competition?

Letting the Dinosaurs Speak—Paleobehavior

Lecture 28

Dinosaurs have been the target of a great deal of misinformation over the years—in books, films, television, and even the scientific community. This lecture aims to address some of the inaccuracies that have emerged in that coverage. We'll discuss the evidence that explains the external appearance of dinosaurs, where they lived, how and on what they fed, their parenting behavior, and the question of whether or not they were warm-blooded.

Reconstructing the Dinosaurs

- A dinosaur skeleton tells us a great deal about its external appearance. The skeleton is the framework on which soft tissues are added. Using comparative anatomy—comparing dinosaurs to tetrapods, for example—we can make some fairly reasonable guesses about what these creatures looked like.
- Muscle scars, which occur on the bone, represent where muscles were attached by ligaments to the bone. Depending on the size of the muscle scar, we can tell how big the muscle was and how powerfully it contracted.
- Skin impressions have been found from a number of species of dinosaur. When dinosaurs died in soft mud, an impression of the skin sometimes became fossilized. Scientists have determined that the scales of dinosaurs were very much like the scales of modern lizards, exhibiting various patterns.
- Pigment is not very well preserved in the fossil record; thus, the coloration in many dinosaur reconstructions is probably fanciful. However, we can assume that dinosaurs weren't just a dull, boring grey. Some dinosaurs had crests, frills, or fringes that probably acted as display features. Given that modern-day lizards also

possess these structures—which are highly colored—many believe that dinosaurs were also highly colored.

What Color Were the Dinosaurs?

- New and exciting paleontological research in determining color from fossils has particular application to the feathered dinosaurs. Dinosaur feathers that evolved for display most likely would have been colorful. Recent fossil discoveries and scientific breakthroughs have provided more definitive information to support this assertion.
- Color pigment is produced in feathers by melanin and structures called melanosomes. Different shapes of melanosomes produce different types of colors. For example, a round-shaped melanosome generally produces blacks and grays, whereas a more elongated, sausage-like melanosome tends to produce more russet colors.
- A research group from the University of Bristol has performed studies on the early feathered *Sinosauroptryx*. This group looked at the melanosomes in the feathers and worked out what some of the colors might have been. The researchers found that *Sinosauroptryx* had a ginger coloring and a striped tail.
- In a more recent study, from a team including researchers from Yale, the dinosaur *Anchiornis* was found to have black, white, and probably red feathers.

Where Did the Dinosaurs Live?

- Unlike the stereotype of dinosaurs wallowing in swamps, many roamed the open ground. Most had long legs placed well under the body and, thus, could run effectively. In fact, the smaller bipedal forms could probably move extremely quickly.
- It's possible that some of the dinosaurs went airborne. *Microraptor*, a feathered dinosaur, was probably climbing up the trunks of trees and gliding between them.

- Some dinosaurs also burrowed under the ground. David Varricchio at Montana State and other researchers have found *Oryctodromeus cubicularis* in fossilized burrows in southwest Montana. Within these burrows, these researcher found an adult and two juveniles—possibly hinting at some sort of parental care.
- Recent research has also discovered semiaquatic dinosaurs. *Baryonyx walkeri*, a spinosaur, came from the Low Cretaceous, about 130 million years ago. It was about 28 feet long, with a crocodile-like snout filled with piercing teeth (not the serrated teeth of a meat eater). Scientists think this creature was a specialized fish eater.
 - Oxygen levels can help us determine whether or not a creature was semiaquatic. Oxygen occurs as light oxygen-16 and heavy oxygen-18. As land creatures lose water through breathing and evaporation, oxygen-16 is preferentially evaporated, which means that the heavy oxygen-18 gets concentrated in the tooth enamel.
 - Because aquatic animals lose less water, less oxygen-18 is present in the teeth. Research by Romain Amiot of the University of Lyon in France found that the oxygen isotope ratio for spinosaurs was much more similar to crocodiles than to dinosaurs. This discovery is controversial, however, because the spinosaur does not show any aquatic adaptations, such as webbing between claws.

What Did Dinosaurs Eat?

- In the broadest sense, dinosaur teeth tell the story. The teeth of *Tyrannosaurus rex*, which look like daggers or steak knives, are clearly designed for eating meat. The teeth of the hadrosaur, in contrast, look more like elephant's teeth: They were adapted for grinding away plant material on the broad surfaces of the tooth.
- Researchers have proposed a number of possible descriptions of dinosaurs' predatory behavior. Larger dinosaurs may have preyed on other creatures much like big cats do today—running down

their prey and killing it swiftly with a single bite or by suffocation. Some dinosaurs may have used an ambush strategy—waylay a creature, wound it, withdraw, and wait for it to go into shock or die from loss of blood. Another possibility is that dinosaurs hunted in packs, as depicted in *Jurassic Park*.



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Dinosaur teeth, such as those of *Tyrannosaurus rex*—obviously designed for meat eating—tell us about their diets, and casts of their brains may give clues about hunting behavior.

- Determining how dinosaurs hunted using only fossil evidence is difficult. Interesting recent studies, however, have attempted to demonstrate how predator dinosaurs hunted their prey. The clues come from dinosaur brain casts, which give us information about the structure and organization of the brain. Scott Rogers at the University of Utah has been studying the anatomical record of brain casts of allosaurs, the top predators of the Late Jurassic.
 - When we compare the brain of the allosaur to its closest relatives—crocodiles and birds—its brain looks more crocodilian than birdlike. The allosaur's olfactory bulbs, where smell is detected, were large, while its cerebrum, the processing area of the brain, was small.
 - *Allosaurus* probably used its keen sense of smell to find its prey and then grabbed it, much as crocodiles do today.

The Softer Side of Dinosaurs

- With regard to parenting behavior, dinosaurs are often depicted like turtles, who lay their eggs and move on, leaving the baby turtles to fend for themselves. Jack Horner, a noted dinosaur paleontologist, has reimaged this notion about dinosaurs.

- In western Montana, Horner discovered Egg Hill, an area with nests of dinosaur eggs and juveniles that had hatched. The nests were made by *Maiasaura*, which means “caring mother lizard.” The nests themselves were closely packed, less than 7 feet apart, and contained about 30 to 40 ostrich-sized eggs, arranged in circular and spiral patterns.
- Scientists don’t believe that this dinosaur sat on the nest but, instead, covered the eggs with vegetation that would give off heat as it started to decompose. It’s possible that, after hatching, the juveniles weren’t able to walk; this behavior implies some sort of parental care by the *Maiasaura* adults.
- We also have evidence of parental behavior in *Psittacosaurus*, a small bipedal dinosaur found in Early Cretaceous rocks. This wonderful specimen was found curled up over 34 juveniles.

Were Dinosaurs Warm-Blooded?

- The traditional, Victorian view of dinosaurs is of slow, lumbering, dim-witted lizards. This view was challenged, most famously, by Robert Bakker. In a paper published in *Scientific American*, “Dinosaur Renaissance,” he proposed that dinosaurs were extremely active, warm-blooded creatures—endotherms, like humans.
- Dinosaur fossils may provide clues. Today’s endotherms—birds and mammals—have limbs brought underneath their bodies. Cold-blooded animals—ectotherms—such as lizards and crocodiles, have a sprawling gait. A dinosaur’s gait is more like that of the endotherms.
- In isotopic evidence, because endotherms maintain a steady body temperature, the ratio between oxygen-16 and oxygen-18 should be constant throughout the skeleton. Ectotherms, in contrast, should have warmer temperatures in the middle and be colder toward the extremities. Analysis of *Tyrannosaurus rex* skeletons shows that the ratio seems to be the same as in endotherms.

- Using an ecological approach, endotherms have to eat more food than ectotherms in order to maintain a high body temperature. For example, a lion has to eat more food than a crocodile; thus, a lion will have a different predator-to-prey ratio than a crocodile. Analysis of the predator-to-prey ratio of the landscape during the time of *Tyrannosaurus rex* gives us information about its metabolic needs. This analysis suggests endothermy—that *Tyrannosaurus rex* was a warm-blooded creature.

The Gigantotherms

- What was the metabolism of the dinosaur's prey? It's likely that large sauropods could not have been endotherms. Their body size was colossal and would have generated far too much heat. These creatures might have had their own special type of metabolism, called gigantothermy.
- For example, mice have a very high surface area-to-volume ratio; thus, they lose a lot of heat. They eat continuously and employ such techniques as shivering to keep themselves warm. Elephants have the opposite problem. They have a very low surface area-to-volume ratio, which means they retain much more heat. They have to radiate a great deal of heat from the body, which is why they have those huge ears.
- Because of their great size, sauropods probably generated a great deal of heat, which allowed them to be more active than the average ectotherm. We can see a similar solution in the cold-blooded leatherback turtle. It can reach sizes of up to 1.1 tons and migrates regularly from the tropics to the poles. The turtle has no problem maintaining its heat at the poles; it has more of an issue radiating heat in the tropics.

Suggested Reading

Bakker, *The Dinosaur Heresies*.

Fastovsky and Weishampel, *The Evolution and Extinction of the Dinosaurs*.

Martin, *Introduction to the Study of Dinosaurs*.

Questions to Consider

1. When we watch modern animated reconstructions of dinosaurs, how much of what we see is pure fantasy, how much is reasonable speculation, and how much is hard paleontological fact?
2. Fossils of dinosaurs demonstrate that some may have possessed quite complex behavior. If they had not gone into extinction, is it possible that some may have evolved to become as intelligent as we are?

Conquering the Air—The Evolution of Flight

Lecture 29

This lecture discusses the prehistoric creatures that left the ground and took flight. Flight has a number of different forms. Passive forms include floating on air currents; parachuting, as a dandelion seed does; or gliding from tree to tree. But the flight we'll discuss here is active—that is, flight powered by a special flight organ: the wing. In addition to wings, the first creatures that left the ground needed light, strong bodies and some form of advanced respiration. This lecture discusses the origins of flight and the first flying creatures and delves into the debate over whether or not birds descended from dinosaurs.

Origins of Flight

- Of all the creatures in the biosphere, the plants probably got into the air first. After all, they were the first out of the water and onto the land. There is evidence of plant spores back to the Middle Ordovician, about 475 million years ago.
- The first animals took to the air soon after the establishment of the land-based ecosystem in the Silurian–Devonian. These were probably floating mites or the juvenile forms of some land arthropods, which would then distribute themselves across the burgeoning new ecosystem.
- The insects were the first to achieve powered flight. But the origins of insect life are obscure, at least from the standpoint of fossil evidence. The first fossilized insects come from the Carboniferous. These dragonfly-like creatures were already well adapted to life in the skies. Like all insects, their wings were composed of dead tissue, making them extremely light.

First Flying Insects

- A clue to how insects got into the air is in the limb system. Early arthropod limbs were paired; these creatures had a walking limb

and a jointed structure behind each limb called an exite. The exite was used for filtering water, or as a gill. The platelike structures on the insect were also used for locomotion; insects often demonstrated these structures in the larval, nymph stage of their life cycles. Such structures were the precursors of wings.

- For indications of the earliest origins of flight, consider one of the most primitive flying insects still with us today: the mayfly.
 - The mayfly, unlike the more advanced forms of insects, cannot fold its wings alongside its body. The nymph stage is aquatic; it has plates along the abdomen that can be flapped in order to increase water movement for respiration, which can be used to propel the creature, as well.
 - These structures appear to be, in some way, preadapted for flight. The insects already have a muscular flapping ability without having to modify an existing limb.

Pterosaurs

- The first vertebrate to get airborne was a Late Permian diapsid reptile, *Coelurosauravus*. Its body had 20 long, curving bones with a skin membrane stretched across it. The bones were jointed at the bases; thus, this creature could probably fold its wings by the side of its body while scurrying up a tree.
- For a vertebrate to move across open areas, however, it needed powered flight. The first vertebrates with powered flight were the



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The mayfly, one of the most primitive flying insects still in existence, provides us with clues about the emergence of flight.

pterosaurs, or “winged lizards.” These creatures were fully flight-capable vertebrates built with air spaces in their bones. Their bones were not only strong but also light—an adaptation that birds would later use.

- The pterosaurs were an extremely successful group, common around the Mesozoic, with a history of 140 million years on the planet. The majority of pterosaur fossils are found in shallow marine sediments. Their fossils are often associated with fishy debris, scales, and bones, so it’s likely that many of them were fish eaters.
- Some pterosaurs developed filter-feeding mechanisms, similar to flamingos. *Pterodaustro* probably used bristle structures to strain microorganisms and algae out of the water. *Quetzalcoatlus*, from the late Cretaceous, was most likely a scavenger, with a wingspan of 33 to 36 feet.
- The oldest pterosaur was *Eudimorphodon*, from the Late Triassic, around 210 million years ago. Like many of the pterosaurs, there’s a suggestion that the beast was covered with a fine, downy hair. Scientists have speculated that these creatures maintained internally generated heat, or were warm-blooded.

Archaeopteryx

- Birds are one of the most successful groups in the history of evolution. They were descended from the archosaurs, which also gave rise to the dinosaurs and the crocodiles. From the hummingbird to the albatross, birds show incredible diversity. They’re highly active and warm-blooded animals. They also have a much more efficient respiratory system than mammals do. Birds actively pump air through the lungs to support their flapping motions.
- The earliest known bird is probably the most famous fossil in the world: *Archaeopteryx*, from the Late Jurassic, about 150 million years ago. The Berlin specimen, now housed at the Humboldt Museum in Germany, was discovered in 1874. It’s preserved in the

Solnhofen limestone that was originally deposited as a rich lime sediment on the edge of the Tethys Sea along an island archipelago. The fine mud preserved the fascinating details not only of its bones but also its body outline and feathers.

- When *Archaeopteryx* was found in this deposit, it caused quite a stir academically. It had many birdlike qualities—feathers, in particular. But other features were very much reptilian. It had a beak full of teeth; a long, bony tail; and claws on the wings. Just as Darwin had predicted, this is a true transition of form from a reptile to a bird.
- *Archaeopteryx*, in all likelihood, was not a strong flyer. We're definitely looking at a transitional form here. One would think that the fossil of *Archaeopteryx* provides an opportunity for us to finally ascertain just how flight came about—from a ground-living reptile to a bird. But the fact is that, even with *Archaeopteryx*, the exact origin of flight is still highly contested and debated.

Ancestors of the Birds

- Consider another fossil found in the Solnhofen limestone: *Compsognathus*, a terrestrial dinosaur. The skeleton of *Compsognathus* is not unlike that of *Archaeopteryx*—but without feathers.
- Thomas Huxley, a famous supporter of Darwin, suggested that birds may have evolved from creatures that resembled small, bipedal dinosaurs. Today, the dinosaur evolution of birds is widely accepted, and in particular, it's thought that birds evolved from the theropod dinosaurs—those bipedal dinosaurs that included everything from little *Compsognathus* to the colossal *T. rex*.
- But this still doesn't answer the question of how dinosaurs may have developed flight. Researchers have put forth two main hypotheses:
 - The arboreal hypothesis suggests that birds evolved from feathered, tree-climbing theropod dinosaurs. The speculation is that they jumped from trees to the ground or from tree to tree, just like a modern-day flying squirrel.

- The curosorial hypothesis speculates that there was an ancestral feathered dinosaur. The feathers originally evolved to keep the creature warm or for display purposes. It is suggested that as this creature ran along the ground, it leapt into the air to catch insects. In that case, the feathered arms became secondarily useful for adjusting body attitude in midair. These creatures may have acquired a flapping motion to help them get up and climb surfaces.

Did Birds Descend from Dinosaurs ... or Not?

- The curosorial hypothesis was the general view until a special fossil—*Microraptor*—was found. It was from the Early Cretaceous, about 120 million years ago, discovered by Xu Xing of the Vertebrate Paleontology Department in Beijing.
- *Microraptor* had feathers on both its forelimbs and its hind limbs. It was a four-winged dinosaur. The feathers on the *Microraptor* were modern looking, asymmetrical around the shaft. This particular structure generates lift. *Microraptor* probably couldn't flap, but it certainly could glide.
- The general view is that such birds as *Archaeopteryx* suggest a close link to the bipedal theropod dinosaurs. But some researchers, including John Ruben of Oregon State University, speculate that birds are only a sister group of the dinosaurs, not descended from them.
 - In Ruben's scenario, birds evolved separately from an archosaur ancestor, developing feathers and flight, as we can see in *Archaeopteryx* and *Microraptor*. Then, some of them lost the power of flight.
 - The result is the appearance of feathered dinosaurs, such as *Velociraptor*, a *Protarchaeopteryx*, which was found later in the Cretaceous. This, according to the hypothesis, would explain why feathered dinosaurs appear in the fossil record only after *Archaeopteryx*.

- This is an area of great debate. Recently, additional feathered dinosaurs discovered in China have been reported to be older than *Archaeopteryx*. Perhaps now, once again, the feathered dinosaurs could be ancestral to birds. The question is, figuratively, up in the air.

First Flying Mammals

- Although flying squirrels are gliders, the best example of a flying mammal—actively flapping its wings—is the bat. Bats are the second most diverse group of mammals (rodents are the first). Bats have a geological history of about 60 million years. They've evolved into many different niches. Some are fruit and pollen eaters; many are insectivores; some are fish eaters; and a small proportion are vampire bats.
- The paleontological record for bats is poor, because their bones are delicate—very light and adapted for flying. There have been some exceptional fossil discoveries, however. For example, *Onychonycteris* dates from 52.5 million years ago. Surprisingly, though, it lacks features around the inner ear used in echolocation in modern bats. The implication here is that it probably had to rely more on sight to hunt insects.
- From what group of animals did bats evolve? The answer to that question is awaiting the true transitional form. *Onychonycteris* was still a bat. The limb proportions and the clawed fingers of this fossil suggest that the common ancestor may have been a good climber.

Suggested Reading

Martin, *Introduction to the Study of Dinosaurs*.

Oregon State University, “Bird-from-Dinosaur Theory of Evolution Challenged.”

University of Manchester, “Prehistoric Birds Were Poor Flyers, Research Shows.”

Questions to Consider

1. Which of the two hypotheses, from the ground up or from trees down to the ground, at first glance appears to be the most logical manner in which flight would evolve in birds?
2. If birds suddenly went into compete extinction, could mammals occupy all the vacated niches?

Monsters of the Deep—Mesozoic Oceans

Lecture 30

In this lecture, we'll consider the oceans of the Mesozoic, 251 to 65.5 million years ago. We'll introduce some of the components of the Mesozoic oceanic biosphere: what was swimming in the vast shoals through the Mesozoic seas, what competed with the corals and sponges in the reef ecosystems, and what were the real monsters of the Mesozoic oceans.

A Dip in the Mesozoic Seas

- The Mesozoic seas teemed with vast schools of fish of all shapes, sizes, and colors. The most common fish today, the bony fish, which had evolved since the Devonian, was abundant at that time.
- The cephalopods were even more plentiful than they are today. The cephalopod (which means “head-foot”) is in the mollusk family, an invertebrate. The terrors of the Ordovician seas were the orthoconic nautiloids, large squids in a conical shell. By the Mesozoic, these had evolved into many different forms, including the belemnites.
- Belemnites looked much like modern squid, but with hooks on their tentacles. The cousins of the belemnites were the ammonites, creatures living in coiled shells. Belemnites and ammonites were common in the Mesozoic ocean.
- Much of the Mesozoic is subdivided, biostratigraphically, into what are known as ammonite zones. Because the ammonites evolved rapidly, produced many short-ranging forms, and were spread across many continents, scientists can use them to subdivide geological finds.

Ammonites

- Ammonites matured by adding a new body chamber to the shell in a kind of a spiral form. The animal lived at the end of the coil in the outermost chamber. Looking at a polished ammonite fossil, we

can see traces of the walls called septa, which are the chambers of the ammonite expressed on the surface of the shell. The traces are suture lines. The most primitive form of ammonites, the goniatites from the Paleozoic, had a simple suture line.

- Ammonites later developed a highly complex, zigzag suture line. It is speculated that a more irregular surface provided a platform to attach muscles to the shell, or that the zigzags were used to brace the shell, allowing the ammonites to dive deeper in search of prey.
- Many ammonites were probably able and swift swimmers. Some of their fossil shells are extremely thin, hydrodynamic objects, designed to slice through water effectively.
- Ammonites are found in many environments, including the open ocean. Scientists are fairly sure that many were ocean-crossing species, which explains why they are reliable for correlation. We find ammonites in very fine ocean sediments with no other shallow-water fossils nearby, indicating a deep-ocean environment.
- The ammonites and belemnites would be gone by the end of the Mesozoic, but during that period, they were an incredibly successful and important part of the Mesozoic oceans.

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Ammonites moved backwards, pumping water at high pressure through a tube called the siphuncle to achieve a kind of underwater jet propulsion.

Rudist Reefs

- After corals were decimated in the Permian–Triassic extinction event, new corals—hexacorals, or Scleractinia—evolved in the Mesozoic. Sponges also became key reef builders during the Mesozoic.

- An important bivalve called the rudist proliferated during the Cretaceous (the last period of the Mesozoic era) and became a component of many tropical reefs. Rudists were particularly prevalent on the margins of the Tethys Ocean. These rudist reefs were many hundreds of feet tall and laterally extensive.
- Why are there no extensive bivalve reefs today? The answer may be found in the ocean chemistry. Many of the Cretaceous oceans were saltier and as much as 14° C warmer than they are today.
- Rudist reefs have been studied in great detail; they are not only unique and interesting but are also of great importance to the oil industry. A rudist reef has many nooks and crannies in it, lots of spaces—a feature called porosity in geology. Given their sizeable extent and high porosity, rudist reefs were ideal places for oil to accumulate.

Ichthyosaurs

- Some of the primitive tetrapods that roamed the Early Devonian landscape gave up their legs and returned to the seas. For example, swimming through the oceans were creatures who looked much like dolphins. These were the ichthyosaurs—streamlined fish eaters and very much reptiles.
- Some ichthyosaurs grew to colossal size; for example, *Shonisaurus* was about 50 feet long. In an extraordinary discovery in Nevada, 37 Triassic specimens of *Shonisaurus* were found fossilized side by side, all pointing in the same direction. Scientists speculate that this might be evidence of a Paleo mass-stranding event, as we witness with whales and dolphins today.
- The ichthyosaur had good eyesight; it had large eye sockets in its skull. It also had odd platelike structures in the eye socket, which were likely adaptations to prevent water pressure from distorting the eye as the creature dived.

- Like dolphins, ichthyosaurs also gave birth to live young. There are quite a number of fossils that actually record the death of a female in the process of giving birth to a fully developed baby ichthyosaur.

Convergence

- The resemblance between ichthyosaurs and dolphins demonstrates an important concept in evolution: convergence. As an analogy, think about how many new automobiles today look similar. The reason is fuel economy: There are certain optimum shapes that reduce drag and maximize efficiency. Tetrapods that live like dolphins will, in all likelihood, look like dolphins, at least on the outside.
- Ichthyosaurs and dolphins demonstrate the concept of convergence beautifully. They're different biologically—one is a reptile, and one is a mammal—but they look similar, even though they're separated by many millions of years. Because they lived in similar environments and likely exploited the environment in similar ways, they look the same.

Mary Anning and Extinction Theory

- A remarkable paleontologist named Mary Anning was the first person to discover and extract an ichthyosaur. In fact, she was also the first person to find a pterosaur outside Germany. As a woman, however, she could not join or even present her research at the Geological Society of London. Even so, Anning would become the world's expert on Jurassic marine reptiles.
- Anning's contributions were significant in another regard. Her work supported George Cuvier's theories about extinction. Cuvier was responsible for developing the useful tool of comparative anatomy; he also speculated that some creatures that had existed in the past were now extinct.
- Extinction was a difficult pill to swallow for some theologians at the time. They thought it implied that there were imperfections in God's creation plan. To get around this problem, some suggested

that the fossil forms that were fading out were probably not extinct—they were just extremely rare. Perhaps they existed in some unexplored area.

- However, the large, impressive creatures that Mary Anning discovered presented a significant problem: Where could they be hiding? Anning's discoveries helped alter the view on how the biosphere has changed over time.

A Modern Mesozoic Monster?

- Another peculiar creature found by Anning was the plesiosaur. They came in two varieties.
 - *Kronosaurus* was a Cretaceous pliosaur that lived around 112 million years ago. About 40 feet long, it hunted fish, ammonites, and probably other marine reptiles, as well.
 - The second group includes the wonderful long-necked plesiosaurs, some of the most iconic of the Mesozoic aquatic reptiles. Like pliosaurs, these creatures used their paddles in a kind of underwater flying.
- The plesiosaur is significant for another reason, however. It is the only Mesozoic aquatic reptile that some say still exists: the Loch Ness monster.
- Is it possible there is a plesiosaur in Loch Ness? There are problems with this hypothesis. First of all, there have been no plesiosaur fossils found from the Cenozoic (the era that followed the Mesozoic). Also, it's unlikely that plesiosaurs could have moved around on land. To be fair, however, paleontologists have been surprised before. Consider the coelacanth: Thought extinct for 65 million years, it was suddenly found living in remote areas.
- A promising explanation for “Nessie” is that the sightings were of sturgeons, ancient creatures that first appeared around 200 million years ago and are still with us today. The sturgeon truly is a living fossil. It has a hump on its back, which could explain the humpback

sightings of Nessie. Perhaps there really is a prehistoric beast living in Loch Ness.

More Monsters of the Mesozoic

- Whatever Nessie's status, plesiosaurs were not the only monsters of the Mesozoic oceans. *Deinosuchus* was a giant alligator. The mosasaur was also gigantic; the largest mosasaur found was *Tylosaurus*, more than 57 feet long. Its jaws were armed with rows of backward-pointing teeth to hold prey securely in its mouth.
- Mosasaurs also had a bizarre-looking additional set of teeth that could hook into the severed flesh of its victim and push it down its gullet. Mosasaurs didn't chew; they gulped. They were probably ambush predators, lying in wait on the ocean floor. Then, using their long tails and powerful flippers, they would swiftly attack the unsuspecting prey from below.
- These extraordinary creatures had vast oceans to explore. During the Cretaceous, the continents were flooded. Europe was reduced to a series of tropical islands, and North America was cut in half from north to south by a shallow body of water. Much of the Sahara was a tropical sea. In the next lecture, we'll explain the reasons for such high sea levels and tropical conditions during the Cretaceous.

Suggested Reading

Ellis, *Sea Dragons*.

Emling, *The Fossil Hunter*.

Questions to Consider

1. Was Mary Anning the tip of the iceberg? How much was science held back by the social and gender attitudes of the 18th and 19th centuries?
2. Why is it that we need monsters, such as Nessie, to exist?

The Cretaceous Earth—A Tropical Planet

Lecture 31

This lecture discusses how we determine what the climate was millions of years ago and examines some of the proxies—signs in the geological record—that can be useful for climatic determination. We'll also look at how we model ancient climates and explore what was driving the Middle to Late Cretaceous climatic system. Finally, we'll discuss the effects of the Cretaceous hothouse climate.

Reading Ancient Climates

- Scientists use a number of different indicators in the geological record to read ancient climatic conditions. For example, cold climates produce glacial striations, glacial dropstones, and sedimentary deposits, such as glacial till.
- Climate conditions are also indicated by the ratio of light oxygen-16 to heavy oxygen-18. In warmer conditions, a great deal of oxygen-16 is evaporated from the oceans and falls onto the land as rain rich in oxygen-16. But during times of glaciation, that oxygen-16 water gets locked up on the land; it doesn't return to the oceans. At those times, the oceans exhibit enrichment in oxygen-18, which is recorded in the fossil shells.
- Extensive red desert sandstones are good indicators of arid conditions. Calcrites, or concentrations of minerals, are also indicators of hot and arid conditions. As water is drawn to the surface and evaporated, minerals are precipitated out of the water to form nodules of such substances as calcium carbonate. Other evidence of hot conditions includes mud cracks, which form polygonal patterns.
- Stomata, or pores, on fossil leaves tell us something about carbon dioxide levels and, by extension, greenhouse effects. The fewer stomata, the higher the carbon dioxide levels—because the plants

don't require that many porous spaces on their leaves to collect the carbon dioxide they need for photosynthesis.

- Leaf shape is a good marker for determining climates. In tropical areas today, leaves tend to have smooth outlines, while in temperate regions, leaves tend to have jagged outlines. Tree rings are proxies for climatic states, as well, with thick rings indicating warm periods and thinner rings indicating cold conditions.

Modeling Ancient Climates

- In contrast to the daily weather, which is ephemeral, climates are defined as atmospheric conditions over longer periods—tens of years, hundreds of thousands of years, or even millions of years.
- Modeling climate is highly complex because so many factors can affect climate. In studying systems that are extremely complex, we need a simplified model that gives us a hypothesis we can test using additional evidence. Climate models are commonly used to predict climate change in the future, but they can also be used to hypothesize about climates of the past.
- The best approach is to create a mathematical model of Earth and its climatic system and then use this model to run tests on various hypotheses. The model created in this manner is called a general circulation model (GCM).
- Even though we possess extremely powerful computers, it is impossible to mathematically model the entire planet. Instead, we break the planet down into model grids. These grids divide the Earth into a series of homogeneous regions, allowing us to more easily calculate the processes and exchanges between them.
- The model uses these factors: the amount of carbon dioxide in the area, the amount of dust (which reflects sunlight), water concentrations, level of solar radiation, and level of radiation reflected back into space from Earth. In addition, the model considers interactions among the atmosphere, the ocean, and the land.

Testing the Model

- The first step of the modeling process is to determine whether the model replicates the conditions we see today. If it doesn't, then the parameters must be changed. Once we have a workable model—a model that seems to reflect what goes on today—we can start to change various parameters and try to make predictions about the future. But we can also reproduce climatic conditions of the past.
- In modeling past climates, the model must account for ancient landforms: paleogeography. Today, the distribution of the continents is extremely important in the way the climate works; this distribution has an effect on the circulation of both global air masses and ocean currents.
- In testing the model, consider Pangaea, about 200 million years ago. If climate models are run for the Late Triassic at 200 million years ago, we get a precipitation pattern that reveals that the interior of Pangaea was extremely dry. This matches the evidence we find in the geological record. At that time, we find many evaporites—salt deposits that form when an open body of water evaporates.
- The center of the continent at this time was a great distance away from the oceans. Because oceans have moderating effects on climate, it appears that Pangaea of 200 million years ago experienced extreme seasonal temperature variations: very hot summers and very cold winters.
- During the summer, air rose over the warm land, creating low-pressure systems. This drew moisture from the warm, shallow Tethys Ocean, creating torrential rains. The reverse occurred during the winter; the land cooled, which caused cold air to form and then sink. Low pressure caused air and moisture to move out over the ocean; thus, the winters were dry and arid. This climatic regime is known as a monsoon. Triassic rocks support evidence of episodic seasonal rainfall.

Ocean Heat Transfer Hypothesis

- At the end of the Mesozoic, during the Middle Cretaceous, about 100 million years ago, there was no ice at the poles and sea levels were considerably higher than today. In contrast to the Triassic, seasonality was much reduced. This is partly explained by the fragmentation of Pangaea. There were more open seaways, which helped modify climatic extremes.
- How did the world arrive at this climatic state? The answer may lie in the oceans. Perhaps the Cretaceous oceans transported more warm waters to the poles than they do today. This is called the ocean heat transfer hypothesis.
- It's speculated that distribution of the continents during the Cretaceous led to intense evaporation of the Tethys Ocean. This generated the formation of dense saline waters. Perhaps the dense, warm, salty water in the tropics sank into the deeper parts of the oceans, which would then act as a conveyor belt, moving warmth from the subtropics toward the poles.
- This is actually the opposite of what drives oceanic circulation today. Today, cold water sinks at the poles, and that drags in warm water behind it, driving oceanic circulation.

The Cretaceous Hothouse

- The source of the extra carbon dioxide that made the Middle Cretaceous so warm was volcanic activity in the mid-ocean ridges. The continents were starting to fragment rapidly at this time.
- There was other volcanic activity, as well. For example, consider the Ontong Java Plateau, a vast undersea volcanic outpouring created by basalts, 19 miles thick in some places. It was at peak activity during the Middle Cretaceous. Like many other mass basalt outpourings, this was probably related to the movement of hot rocks from the Earth's mantle—producing a great deal of carbon dioxide.

- The Cretaceous hothouse environment had a profound effect on the Earth. Because there was no ice at the poles, most of Earth's water stayed in the oceans—meaning extremely high sea levels. Mid-ocean ridges were very active, producing a lot of material that displaced water, which sloughed onto the sides of the continents.
- The oceans at this time were very warm. Warm water occupies more volume than cold water because of the thermal expansion coefficient. Sea levels were probably the highest seen in half a billion years, with many continental interiors extensively flooded. The flooding formed warm, shallow continental seas.
- Large seaways penetrated North America and Africa. Much of Europe was just a series of tropical islands. These seaways helped moderate the continental climatic effects.

Chalk Seas

- Because the shallow, warm oceans were extensive and far from continental input of sediment, they were ideal locations for certain tiny marine creatures to flourish.
- The coccolithophores were photosynthetic algae about 5 to 10 microns across. They secreted a calcium carbonate skeleton and lived in the photic zone of the ocean—the depth to which sunlight can penetrate. When they died, their skeletons sank to form extensive sedimentary deposits.
- The calcium carbonate from their skeletons formed calcareous ooze. This was only possible if the seas were shallower than the carbonate compensation depth (CCD). The result: chalk.

Polar Dinosaurs

- Another important feature of the greenhouse world is the fact that warmer temperatures permitted the existence of dinosaurs in polar regions. Dinosaur Cove in south Australia, from about 106 million years ago, represents a floodplain deposit on a developing rift



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The famous white cliffs of Dover are almost 100 percent coccolith.

valley. The rift valley was part of a rift system that would eventually separate Australia from Antarctica. Australia then drifted northward to become the island continent it is today.

- Although not glacial, temperatures were certainly not tropical. They were just warm enough for extensive forests, where the dinosaurs lived. It's likely that many species of dinosaur migrated to warmer locations during the winter but perhaps hibernated during colder times.
- An example of a polar dinosaur from this part of Australia—which would have been within the Antarctic Circle during the Cretaceous—is *Leaellynasaura*. This dinosaur had extremely large eyes—perhaps adapted for seeing in low-light conditions during the polar night. It is possible that these animals were warm-blooded and foraged for food during the winter. Never before or since have creatures acknowledged as reptiles been so close to the poles.

Suggested Reading

Ruddiman, *Earth's Climate*.

Wicander and Monroe, *Historical Geology*.

Questions to Consider

1. Are the grid models that are used to predict and model climate too simplistic to be of any real use?
2. Does the climatic system during the Cretaceous have anything to teach us about current climate change, or is the Cretaceous world just too remote?

The Sky Is Falling—End of the Dinosaurs

Lecture 32

The Cretaceous–Tertiary extinction event dates to about 65.5 million years ago. It is generally known as K-T. (In German, the translation for Cretaceous is spelled with a *K*; the *T* stands for the period following the Cretaceous, the Tertiary.) The term Tertiary was removed by the International Union of Geological Sciences; the event is now known as the Cretaceous–Paleogene extinction event, or K-P. Of all the extinction events in paleontology, the K-P is probably the most studied. This mass extinction event, which may have been precipitated by a massive fireball, killed off all the dinosaurs.

The K-P Extinction Event

- In addition to the dinosaurs, many other creatures—50 percent of all species—were lost in the K-P extinction event. On land, few creatures weighing more than 25 kilograms survived. There are notable exceptions to this, however, such as crocodiles and alligators.
- The reason these animals are still with us today is that they are generalists: They will eat virtually anything. They can also survive for long periods with absolutely no food at all. Specialists are the ones that suffer the most in extinction events. At the end of the Cretaceous, the generalists made it through to the Paleogene. Many of those generalists were mammals.
- The K-P extinction event was even more severe in the oceans—killing off 80 to 90 percent of species. All those magnificent marine reptiles—plesiosaurs, pliosaurs, and ichthyosaurs—and the ammonites and other cephalopods would be gone forever.

A Thin Layer of Clay

- The study of this extinction event is linked to a story of a father and his son: Luis Alvarez and his son, Walter. Luis Alvarez received

the Nobel Prize for his work on particle physics. His son, Walter, became a geologist at the University of California, Berkeley, studying sedimentary rocks in the province of Umbria near Gubbio in Italy.

- Gubbio is a key location for geologists and paleontologists: The limestone cliffs that surround the town record the transition from the Cretaceous to the Paleogene. Rocks in that area cross the extinction event. A cleft in the rock marks the exact position of the transition from the Cretaceous to the Paleogene. The transition is marked by a very thin layer of clay, about 0.4 inches wide.
- The area below the cleft contains dinosaurs and ammonites, but above it, they are gone forever. Walter Alvarez took a sample from the clay section that crosses the K-P boundary and asked his father for help. They asked how long it took for the clay to be deposited. Did it accumulate slowly over millions of years, or did it represent a rapid event—something that was deposited in a geological blink of an eye?

The Iridium Spike

- The answer lies in a methodology for calculating the accumulation rates of sediments that uses the rare element iridium. Although iridium is scarce in the Earth's crust, our planet receives a continual rain of micrometeorites rich in iridium; thus, the iridium accumulation rate is known.
- The Alvarez team used neutron activation analysis to determine the amount of iridium in the clay sample. They were astounded by the results. What they found was a massive spike in iridium levels right at the level of the clay but not in the limestone below or above it.
- The sheer volume of iridium could not have accumulated through slow processes. There was really only one reasonable explanation: There was a delivery source with a high concentration of iridium—something like a very large meteor or comet. This theory of a massive impact from space was further supported by the global

distribution of this clay layer containing iridium. It was found virtually all over the world.

Supporting Evidence for the Impact

- Such a controversial hypothesis—a massive impact from space—warranted further questioning and testing. Scientists looked for other signals of this impact event—something beyond a thin layer of clay rich in iridium. Fortunately for the Alvarez team, a great deal of supporting evidence was found.
- Among the first plants to colonize an area after fire devastation are ferns. When they reproduce, they release spores, which then become incorporated in the sediments around that area. A vertical core of sedimentation will indicate times when many ferns were producing lots of spores. Each of the spikes found in that core can be a proxy for fire devastation. In fact, just after the K-P boundary, all over the world, a large spike in fern spores has been noted.
- Other important features were found in the clay layer: tektites and microspherules. These are produced by molten rock splashing out of an area after a large and energetic explosion. Tektites often take a teardrop shape. Microspherules represent a fine spray of multi-material. Interestingly, a concentration of these features was found between North and South America.



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The fact that a large spike in fern spores appears globally indicates that almost the entire world experienced fire devastation at the end of the Cretaceous.

- Another piece of evidence comes from shocked quartz, which develops crosshatched lines in large, energetic explosions. Shocked quartz is also present in high concentrations between North and South America.
- Sedimentary rocks reveal that at the end of the Cretaceous, there was a mega-tsunami—one so huge that it cannot be explained by normal phenomena. Something at the end of the Cretaceous created tsunamis that penetrated very deep into the continental interiors. The evidence points toward a potential impact in the ocean.

The Chicxulub Crater

- Based on the iridium present in the clay layer, the Alvarez team speculated that the impacting body would be more than 6 miles in diameter. An object this size could not have been vaporized in an airburst; this one would have left a very large hole. But the final piece of evidence—the crater—was still missing.
- There was a crater, but it was not known to the Alvarez team at the time. In 1951, a Mexican company was drilling off the coast of Mexico around the Yucatán Peninsula. The deeper the workers drilled, the stranger the rocks became. They started to see evidence of fracturing and melting of rocks, and at the very lowest levels of the drill core, the rocks were completely melted.
- In 1978, geophysicists looking for structures indicating the presence of oil found a large circular structure around the coastline of Yucatán, which they imaged using gravity and magnetic analyses. However, due to company confidentiality, they were prevented from releasing the data until 1981. Coincidentally, this was the same year that the Alvarez team published the impact paper.
- The crater—called Chicxulub Crater (meaning “tail of the devil” in Mayan)—is about 112 miles across. Tektites and shocked quartz become thicker toward the structure. Analysis of the crater suggests the cosmic body had a fairly shallow entry, at about 20 to 30

degrees. Any more shallow and we might still have dinosaurs with us today. The rock was probably about 6 miles in size. Think of Mount Everest suddenly being slammed into the Yucatán Peninsula.

- Further evidence in the form of ejecta was found. The impacting body entered from the southeast, which meant that most of the ejecta was thrown out to the northwest. In fact, Texas is blanketed with a thick layer of crater debris.
- The energy released was the equivalent of about 6.2×10^7 tons of TNT. That kind of explosion does not simply fracture or melt rock; it vaporizes it. It is estimated that about 62 cubic kilometers of rock was literally vaporized in a flash.

Last Day of the Cretaceous

- At the moment of impact, there was a detonation, a pulse of intense heat and light, vaporizing everything close by. Any organic material farther away spontaneously combusted. The Earth rang like a bell with seismic energy. The shock wave hurled superheated rock debris and molten material around the globe. It generated the largest tsunami seen in more than 600 million years.
- This was only the start of the impact story, however. Millions of tons of dust and debris were thrown up into the atmosphere, where it would stay suspended, perhaps for many months. This caused the Earth to cool and photosynthesis to cease.
- Even after the dust settled, the times of cold and darkness severely affected plant life. Consequently, herbivores starved, and the carnivores followed. The ecosystem would collapse.
- Much of the rock that was vaporized was limestone, or calcium carbonate. When limestone is vaporized, it creates carbon dioxide. The climate would flip-flop rapidly from cold, dark conditions lasting for months, to hot conditions lasting for decades or even longer.

- Even worse, the high-yield detonation physically burned the air, combining oxygen and nitrogen to form oxides of nitrogen. These would dissolve in water in the atmosphere and then fall to the Earth as dilute nitric acid—further polluting the soils, killing off more plants, and affecting the base of the food chain to an even greater degree. By the time this particular catastrophe had concluded, 50 percent of the species on Earth were gone.

A Stressed Biosphere

- Although the impact theory is very compelling and widely accepted, many scientists are still uncomfortable with an impact-only extinction hypothesis. Some forms, such as microplankton and dinosaurs, correlate precisely with the extinction event, but other groups, such as the ammonites, were already in decline.
- It has been suggested that the Cretaceous biosphere was already stressed by volcanic activity. The K-P impact represented the final nail in the coffin. It eradicated some of the most magnificent and astonishing creatures that have ever lived—the dinosaurs.
- But if the dinosaur origin of birds holds true, it is possible that the K-P event witnessed the extinction of only non-avian dinosaurs.
- In the next lecture, we will examine some of the creatures that would eventually inherit the Earth from the dinosaurs: the mammals.

Suggested Reading

Bakker, *The Dinosaur Heresies*.

Fastovsky and Weishampel, *The Evolution and Extinction of the Dinosaurs*.

Freie Universitaet Berlin, “Prolonged Climatic Stress Main Reason for Mass Extinction 65 Million Years Ago, Paleontologist Says.”

Hallam, *Catastrophes and Lesser Calamities*.

Imperial College London, “Asteroid Killed Off the Dinosaurs, Says International Scientific Panel.”

Questions to Consider

1. If an impact event of the scale of the K-P was to occur today, would you put your money on rats or pandas to survive the extinction? With this in mind, how do you think *Homo sapiens* would fare?
2. Do you think the impact of a body the size of Mount Everest is sufficient to have caused a mass extinction event, or do you think a combination of factors that includes impact is more likely?

The Collision of North and South America

Lecture 33

A recurring theme of this lecture series is the interconnectedness of all the Earth's systems. The interplay of these systems has resulted in periods of glaciation, changes in ocean chemistry and atmospheric composition, and mass extinction events; however, interactions between Earth's systems do not always result in catastrophic global mass extinctions. Sometimes, we see a gradual turnover in species. This lecture examines what happened in the Americas—particularly South America—in the period just after the dinosaurs, when other extraordinary creatures inherited the Earth.

Effects of Isolation

- By the time of the Cretaceous–Paleogene extinction event 65 million years ago, the configuration of the continents was very modern and familiar looking. South America and North America were separated; there was no definitive land bridge between the continental masses. Central America was probably a peninsula of North America, and most likely, a series of islands sat between North America and South America. Sea levels were still fairly high.
- In South America, the geosphere had a profound effect on the biosphere. For most of the Mesozoic and Cenozoic, the history of South America was one of isolation. Like Australia, which was a lifeboat for the marsupials, South America also protected unique creatures from waves of new forms that migrated throughout other parts of the world.
- Because South America was isolated from the other continental landmasses by at least the Middle Cretaceous, it preserved many Early Cretaceous and perhaps some of the Late Jurassic dinosaurs and mammals that went extinct in other parts of the world.

Evolution of the Australian Megafauna

- During the Late Cretaceous, marsupials (pouched mammals) and placental mammals (the group humans belong to) were probably able to swim or raft on mats of vegetation between islands. Scientists believe that a certain marsupial in South America migrated all the way to Australia via Antarctica about 50 million years ago.
- It has been suggested that from that initial wanderer—a relative of the South American marsupial known as the little mountain monkey, or *Dromiciops*—a radiation of Australian marsupials took place, giving us kangaroos, koalas, and wombats.
- An evolution also took place of Australian marsupial megafauna—a unique group of large Australian animals that would grace the continent 1.6 million to 50,000 years ago. Most of them would be extinct by around 46,000 years ago, which appears to match the timeline of the arrival of humans in Australia. It has been suggested that a combination of burning the landscape to drive prey and hunting itself eventually led to the demise of these large creatures.

Meet the Australian Megafauna

- *Genyornis* was a class of flightless birds, some of which may have been carnivorous. *Megalania* was a giant monitor lizard, about 23 feet long. *Meiolania* was an 8-foot turtle that had various horns and protrusions on its shell.
- Giant marsupials were in existence, as well.
 - *Diprotodon* was a rhino-sized wombat, about 10 feet long and 6.5 feet at the shoulder. It inhabited open woodland and grassland areas, eating leaves, shrubs, and grasses.
 - The giant short-faced kangaroo, *Procoptodon goliah*, was about 6.5 feet tall. It had teeth adapted for chewing tough desert plants and could probably jump much higher than modern kangaroos.
 - Another relative of the modern kangaroo was *Propleopus oscillans*, an opportunistic omnivore with large shearing teeth.

- The marsupial lion, *Thylacoleo carnifex*, weighed about 220 pounds and had large slicing cheek teeth and a retractable thumb claw.

Convergent Evolution

- Following the continental isolation of South America 80 million years ago, the animal population evolved independently for 60 million years, with just the occasional invader. As a result, South America would develop a unique ecosystem. Some of the South American marsupials, such as the opossum, can be found in North America today.
- Many creatures from this time, however, have gone extinct.
 - The rabbitlike mammal *Protypotherium* was probably an agile burrower, like modern rabbits. *Protypotherium*, like many South American forms, demonstrates convergent evolution—a situation in which creatures that belong to different groups start to resemble each other because they occupy similar ecological niches.
 - The horselike mammal *Diadiaphorus* had three toes, one of which touched the ground like a hoof.
 - The camel-like mammal *Macrauchenia*, first discovered as a fossil by Charles Darwin, was about 10 feet long and had a bizarre short trunk on its face.
 - *Thylacosmilus* belonged to a sister group of the marsupials and was probably one of the most dramatic examples of convergent evolution between North America and South America. It was a 330-pound predator—the South American equivalent of the North American *Smilodon*, a saber-toothed cat.
 - Other top predators that preyed on the giant marsupials were borhyaenids. They were definitely marsupial-like, with a pouch to carry their young. They were about 5 to 6 feet long and had

strong, bone-crunching jaws. The borhyaenids resembled a large Tasmanian devil.

- *Glyptodon*, a heavily armored animal, was about the same size and weight as a Volkswagen Beetle. *Glyptodon* was another example of convergence with the ancient creature *Ankylosaurus*, a Late Cretaceous dinosaur common in western North America.
- Perhaps the most iconic animal of the South American fauna was a fossil found by Charles Darwin during his voyage on the HMS *Beagle*: *Megatherium*, an elephant-sized ground sloth weighing around 6 tons.

Invaders from Africa and North America

- The continental mass of South America was not completely isolated, however; there was the occasional invader. For example, about 31 million years ago, during the Oligocene, animals began to arrive from abroad—but not from North America. They came from the Old World: Africa. The Atlantic Ocean was not as wide as it is today, and species may have arrived on drifting plant material.
- These pioneers from Africa included rodents that would evolve in South America as the capybara and the chinchilla. About 25 million years ago, primates arrived in South America and diversified into New World monkeys.



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New World monkeys, such as the squirrel monkey, originated in Africa; their ancestors may have arrived in South America as passengers on drifting plant material after heavy rains or flooding.

- Tortoises were another invader from Africa. Even after they arrived in South America, they continued across the continent and embarked on another sea journey, floating out into the Pacific and eventually colonizing the Galápagos Islands. They would diversify into a number of forms there, where Charles Darwin eventually encountered them—an event that initiated his theory of evolution.
- Around 6 million years ago, creatures related to raccoons started to invade South America from North America. *Chapalmalania* was a 5-foot, bearlike raccoon. These migrations were not just one way, however. *Megatherium*-like ground sloths worked their way to North America by about 9 million years ago.
- Another import to North America was the flightless pterodactyl bird called *Titanis walleri*. Around 8 feet tall, it arrived about 3 million years ago. It probably had a large, powerful, hooklike beak.

The All-Important Isthmus of Panama

- Over time, South America drifted toward Central and North America, and the ocean plate below the Pacific became subducted below the Caribbean plate. Above this line of contact, a series of volcanic islands developed. Sediments eroded from the islands and from both North America and South America gradually filled in the gaps between the continents, forming the Isthmus of Panama. This land link would have serious consequences for South American fauna and, indeed, for the rest of the world.
- By 3 million years ago, the land bridge was in place. It enabled an easy exchange between North America and South America. Camels, elephants, bears, deer, tapirs, skunks, rabbits, cats, dogs, kangaroo rats, and shrews all made the journey from North America to South America. Moving from south to north were monkeys, opossums, anteaters, sloths, armadillos, porcupines, and glyptodonts.
- Unfortunately, the result was a net overall extinction of the South American forms. The pterodactyl birds were mostly outcompeted by cats

and dogs from North America. *Thylacosmilus* was outcompeted by its North American counterpart *Smilodon*. The giant bearlike raccoon was replaced by real bears, and most of the savanna grazers were replaced by their North American equivalents. The only truly successful migrants northward were armadillos, opossums, and porcupines.

Creatures Toughened by Competition

- What's the explanation for this asymmetry? Why did the South American forms fare so badly? Scientists speculate that the reason was climate. Creatures that could survive tropical conditions in Central America found similar conditions southward. Those traveling north, however, quickly encountered far drier and eventually colder conditions—placing a cap on their migration.
- There may have been a more profound reason, as well—a reason that concerns the playing field of evolution of both groups.
 - South America had been isolated; thus, competition would come only from within that landmass. North America was not only physically larger, but it also had a landmass near today's Alaska—called Beringia—that linked North America to Asia.
 - Beringia was about 1000 miles wide; this large corridor was particularly important during ice ages, when sea levels fell. It was not glaciated and probably experienced only light snowfall; it was a large grassland steppe, ideal for the migration of creatures.
 - Creatures from as far away as Africa were free to migrate, mix, and mingle with North American forms. The result was a much tougher proving ground for North American animals. In the waves of migration forcing natural selection, we look at the survival of the fittest. The South America native fauna suffered badly because they found it difficult to compete with the battle-hardened northerners.

Changes in the Ocean

- Consider the wider consequences of the formation of the Isthmus of Panama in the context of Earth system science. First, the oceans would experience the opposite of migration; they would experience what has been called the great schism.
- The great schism halted the mixing of Pacific Ocean and Caribbean Sea creatures, which led to independent evolution in some marine forms. In addition, the elimination of nutrient-bearing currents from the Pacific into the Caribbean led to extinctions in forms dependent on those nutrient-rich waters.
- By about 2.6 million years ago, the ice was back. In the next lecture, we will see how the Gulf Stream was changed by the Isthmus of Panama. We will also see how mammals evolved after the dinosaurs—and, ultimately, how they would cope with the return of the glaciers.

Suggested Reading

Gould, ed., *The Book of Life*.

Kemp, *The Origin and Evolution of Mammals*.

Smithsonian Tropical Research Institute, “Sex in the Caribbean.”

Questions to Consider

1. Were the South American marsupial mammals an inherently inferior form of mammal compared to their North American placental cousins? Alternately, was their general extinction a result of the greater competition that the North American forms had to deal with before crossing the Isthmus of Panama?
2. How many events like the formation of the Isthmus of Panama have had profound effects on the history of life on Earth, and how many of these events are missing from the geological record?

The Rise of Mammals and the Last Ice Age

Lecture 34

This lecture deals with the evolution of mammals in the Cenozoic era, following the extinction of the dinosaurs. Mammals actually evolved about the same time as the dinosaurs, in the Late Triassic, around 200 million years ago, but were outcompeted during the Mesozoic. In this lecture, we'll discuss the nature of the mammalian radiation of new forms after the dinosaurs; the return of Earth to a grip of ice; and what happened to the mammalian megafauna.

The First Mammals

- Mammals probably evolved from cynodonts, a group of synapsid reptiles. Cynodonts may have had the first indications of mammalian characteristics, such as whiskers and fur.
- One of the earliest mammals in fossil form was the mouse-sized *Megazostrodon* from the Late Triassic. Most likely a nocturnal insectivore, it also probably laid eggs like its cynodont ancestors.
- Some early large mammal forms were found in the Triassic, such as *Repenomamus*, about 1 meter long. Some of its fossils have been found with a stomach full of young dinosaurs. At this time, however, mammals in general were restricted to the undergrowth, scurrying around the feet of the dinosaurs.
- One reason that mammals were not very diverse through the Mesozoic was that the dinosaurs already occupied all the ecological niches. This placed a kind of evolutionary cap on the diversification of the mammals.
- Even after the extinction of the dinosaurs, mammals remained relatively small insectivores. They did not achieve even moderate sizes until long after the end of the Cretaceous.

A Forest World

- During the Early Paleogene, the Earth was much warmer than it is today. The tropics and subtropics extended farther north and south; deciduous trees grew fairly near the North Pole.
- One hypothesis for the lack of mammalian radiation is that much of the Earth at this time was covered in dense forests. This environment reduced the variety of ecological opportunities for mammals to exploit.
- Temperatures continued to increase through this period, reaching a high point about 56 million years ago. Temperatures increased by about 6 degrees over 20,000 years. Fossil alligators have been found near the North Pole, and palm trees have been found in parts of Alaska.
- The first primitive doglike mammalian carnivores appeared at this time: mesonychids. This period also saw primitive horses, as well as primates. A transitional form at this time was *Ambulocetus* (meaning “walking whale”—a four-legged creature that swam but was quite able to walk on land. It’s likely that all the whales and dolphins in today’s oceans evolved from *Ambulocetus*.

The Messel Pit

- One of the best windows into this tropical forest world of the Eocene is the Messel Pit in Germany. Not only is it a site for coal and oil shale extraction, but it also preserves a remarkable suite of fossils.
- During the Eocene, about 47 million years ago, this area was tropical forest surrounding a series of lakes. The bottom of those lakes became rich in organic debris, hence the abundance of coal and oil shale. Because of the anoxic bottom environment, creatures that fell into the lake and settled had a high probability of becoming fossils.
- The Messel Pit contains a number of mammal fossils. *Archaeonycteris* was a primitive bat. *Leptictidium*, about 24 to 36 inches long, was bipedal. We also find *Propalaeotherium*, a cat-

sized ancestor of the horse. Most of the mammal fossils are small, probably because of the dense forested environment.

Warming during the Eocene

- What were the causes of high temperatures during the Eocene? Because there was more carbon dioxide gas in the atmosphere from volcanic emissions, there may have been an increased greenhouse effect.
- An intriguing possibility, however, is that high temperatures resulted from burning peat; the Paleocene is known for high peat accumulation. Changes in the Earth's orbit may also have helped keep the planet warm.
- Whatever the cause, the warming may have destabilized clathrates—methane gas trapped in ice. The released methane would increase the greenhouse potential for the planet. At this time, the world was at its warmest. Following the Eocene, the Earth moved into a long period of global cooling.

Rise of the Mammals

- By the end of the Eocene, mammals started to dominate the Earth. Some of the most spectacular developments occurred in the oceans. For a number of creatures, legs disappeared and became flippers. These creatures diversified into a series of fully aquatic mammals. *Basilosaurus*, about 52 feet long, was the apex predator in the Eocene oceans—a worthy successor to the mosasaurs of the Cretaceous.
- The climate was shifting, however. By the Oligocene, around 43 million years ago, there was ice at both poles. Sea levels began to drop. The world was still warm, but it was getting more seasonal. The steamy, lush jungles of the Eocene were replaced by a more open landscape.
- During the Oligocene, many of the modern frogs and insects evolved. Apelike and monkeylike primates would make an

appearance. Carnivora, the modern meat-eating mammals, would replace earlier carnivorous mammals, such as *Andrewsarchus*.

Earth Returns to the Grip of Ice

- By the Miocene, about 23 million years ago, the biosphere was starting to look quite modern. Grasses and herbs spread in an increasingly seasonal climate. The rhino and horse families became less common, replaced by deer and the Bovidae: antelopes, sheep, goats, and cattle. Carnivores began to take on their modern forms.
- There would be a brief return to warm conditions in the Early Pliocene, but about 2.5 million years ago, Earth entered the current ice age. This ice age would comprise a number of glacial and interglacial periods.
- As the Earth entered the current ice age, three ice caps formed: over North America, Greenland, and Scandinavia. Today, only the Greenland ice cap survives.

Isthmus of Panama

- The cause of this glaciation is still a matter of debate. Carbon dioxide levels had dropped, but that was 2 million years before the ice age. Scientists believe the trigger factor for the most recent ice age was the creation of the Isthmus of Panama and its effects on the Gulf Stream.
- The Gulf Stream is a rapidly moving warm ocean current. It forms around Florida and follows the east coast of North America. It then moves out into the Atlantic Ocean and toward northern Europe. It was famously mapped by the polymath Benjamin Franklin, who also gave the Gulf Stream its name.
- Today, trade winds carry water evaporated from the Atlantic to the Pacific, making the Atlantic more saline than the Pacific. This also makes the Gulf Stream denser, which causes it to sink just north of Iceland.

- Before the formation of the Isthmus of Panama, the waters of the Pacific and the Atlantic were free to mingle; the salinities in the Gulf Stream were lower and the water was less dense. This permitted the warm waters from the Gulf of Mexico to flow farther north, keeping the Arctic free of ice. When the isthmus formed 3 million years ago, ice soon began to develop in the northern hemisphere.

Effect of Orbital Mechanisms

- Milutin Milanković, a Serbian civil engineer and mathematician, put forth an explanation for the cycle of glacial advances and retreats. He speculated that the Earth's movements through space affected the amount of solar radiation reaching the surface of the planet and, by extension, past climates.
 - The eccentricity cycle, a period of about 90,000 to 100,000 years, describes how the Earth's orbit changes from a circular orbit, in which conditions will be warmer, to an elliptical orbit, in which they will be cooler.
 - Obliquity describes the axial tilt of the Earth. The maximum tilt is 24.5 degrees; the minimum is 22.5 degrees. Today, we're at about 23.5 degrees. To move from the maximum tilt to the minimum tilt takes about 41,000 years. During times of minimum tilt, the polar regions get the most heat from the sunlight during the summer.
 - The precession cycle, about 26,000 years, describes the way the Earth's axis moves—like a wobbling top or a gyroscope.
- Milanković speculated that if all those cycles combined to a point where the Earth was receiving minimal sunlight and coincided with low levels of carbon dioxide, a perfect storm of cooling would result.

Land Bridges Appear

- The glacial periods appear to match the orbital forcing mechanisms. The last glacial advance was 35,000 to 12,900 years ago, peaking

about 20,000 years ago. Sea levels dropped considerably and large areas of low-lying land opened up.

- Beringia appeared between North America and Asia; Doggerland appeared between the United Kingdom and Europe. These vast areas of open grasslands allowed creatures to migrate freely.
- The spectacular megafauna that evolved in a cooler and drier world are familiar to us: wooly rhinos, mastodons, and mammoths.
- With spectacular megafauna herbivores come spectacular megafauna carnivores. The short-faced bear, the apex predator of this environment, was at least 21 percent larger than a Kodiak bear. One of the most iconic creatures of this time was *Smilodon*, the saber-toothed cat.

Megafauna Become Extinct

- The megafauna disappeared rapidly 15,000 to 10,000 years ago. In North America, 33 taxa became extinct; in Eurasia, about 21 taxa became extinct. This was not a mass extinction event, but it did seem to target the big creatures. Another important factor that we have not considered was the emergence of a new super-predator: humankind.
- The Lascaux Cave paintings in France illustrate that humans coexisted with these enormous creatures. In North America, the appearance of the Clovis culture coincides with some extinctions in the megafauna. A combination of climate change and overhunting probably led to the animal extinctions.
- In Africa, many of the megafauna—such as giraffes and elephants—still exist, perhaps because they coevolved with humans. When humans migrated to Europe and North America, however, they encountered fauna that lacked the behavioral adaptations that would allow them to survive this new wave of super-predators.



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Cave paintings reveal that humans coexisted with megafauna; human hunting at this time may have driven some creatures to extinction.

- Despite setbacks, the mammals flourished, at least partly because—unlike fish, amphibians, and most reptiles—they have highly differentiated teeth. This allows them to adapt to a variety of diets and environments.
- In the next lecture, we'll examine the story of one particular mammal group: us.

Suggested Reading

Kemp, *The Origin and Evolution of Mammals*.

Martin, *Twilight of the Mammoths*.

Questions to Consider

1. Do you think we underestimate or overestimate our species impact on the planet?

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2. How much of the recent story of the biosphere and our own part in it may now be drowned below the waves?

The Humble Origins of Human Beings

Lecture 35

As Charles Darwin learned, the origins of the human race can be a touchy subject. In his famous 1859 book, *On the Origin of Species*, Darwin deliberately left human origins alone, stating, “light will be thrown on the origin of man and his history.” More than any other individual species, humans have had a profound effect on the Earth’s systems. This lecture looks at the place of humans on the tree of life; the early origins of our family, the primates; the end of the golden age of the apes; and the nature of the first ape men.

Humans on the Tree of Life

- Humans belong to a mammal group, the primates, that includes lemurs and tarsiers. Within the primates, we are Anthropoidea, or higher primates, a group that includes monkeys and apes. Within the anthropoids, we belong to the Hominidae, or great apes, which includes gorillas, chimpanzees, orangutans, and gibbons. Along with chimpanzees, we form the Hominini, and within that group, we are the sole surviving representative of the genus *Homo*.
- Under the Linnaean scheme, we had the Hominidae all to ourselves. All the other great apes were excluded to reflect the special status of humans and our differences from the apes.
- Under cladistic analysis, though, we cannot solely claim the Hominidae. Chimpanzees, gorillas, and orangutans all have to be included; otherwise, the grouping is not valid under cladistic schemes. Genetically, humans are not that different from the rest of the apes; we are, after all, more than 98 percent chimp.
- With this in mind, however, we’ll investigate the origins of just one species in all of Earth’s history, *Homo sapiens*. We will see how a small genetic difference—less than 2 percent—can affect a species.

Origins of the Primates

- One of the earliest ancestors of the primates was a shrewlike creature called *Purgatorius*, about 6 inches long. The characteristics of its teeth definitely identify it as a primate. We think that this creature was likely a diurnal insectivore.
- *Purgatorius* was recovered from the Hell Creek Formation in Montana. Originally thought to be Late Cretaceous, the formation was later determined to date from about 63 million years ago, just after the extinction of the dinosaurs. Even so, it's thought likely that the ancestors of the primates evolved during the time of the dinosaurs.
- Moving forward in time, to 58 million years ago, we find *Plesiadapis*, a fairly small mammal with chisel-like incisors and a long snout that makes it look more like a rodent than a primate. Preserved fossils suggest that this animal was more of a ground dweller than a tree dweller.
- An example of an early tree-dwelling primate was *Dryomomys*, from about 56 million years ago. It was about the size of a mouse.

The Foramen Magnum

- By the Eocene, 56 to 34 million years ago, we start to see early primates: the prosimians. They were well established in dense tropical forests that covered much of the planet. Various lemur-like creatures evolved in this environment.
- A famous fossil from this time caused a stir in 2009: *Darwinius masillae*, or Ida—47 million years old and recovered from the Messel Pit fossil deposits. Ida was hailed at the time as one of our most direct ancestors. Many now believe that it's only distantly related to humans and probably more directly related to lemurs and lorises. Even so, Ida gives us a clear picture of what was leaping in the Eocene tree canopies.



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Hominids did not have large brains; it would seem that standing erect is what first drove humans on the path away from other apes.

- An important change is noted in some fossil forms. Bipedal creatures have a large opening, called the foramen magnum, in the base of the skull that connects to the spinal cord. In humans, the skull is balanced on the top of the spine. However, in such tetrapods as cats and dogs, the spine is essentially horizontal, with the foramen magnum more toward the back of the skull.
- Some fossils from this time show the foramen magnum starting to move forward. Early primates were possibly developing a kind of bipedal locomotion—an important sign of what was to come.

The Golden Age of Apes

- By the Miocene period, 23 million years ago, monkeys had evolved. One of best known forms was *Aegyptopithecus*, about the size of a house cat. These monkeys, technically known as anthropoids, probably outcompeted and replaced the earlier prosimians.

- Up to about 8 million years ago, the world could be described as the golden age of apes. A diverse group, the apes made up more than 50 species. Some, such as *Sivapithecus*, were large; others, such as *Limnopithecus*, were tiny and probably lived high in the treetops. About 7 to 8 million years ago, however, this golden age of apes suddenly came to an end.

Piltdown Man

- Early paleoanthropologists speculated that what drove human evolution was human intelligence. It's what separates us from the rest of the apes. These paleoanthropologists thought that the missing link between the apes and humans should look like an ape but have a large brain.
- In 1912, Charles Dawson, an amateur archaeologist, found what he claimed was this missing link: Piltdown Man. The remains Dawson discovered had a human-sized brain over the face of an ape.
- The scientific community at the time was utterly persuaded. Piltdown Man was exactly what was and would remain the touchstone for understanding human evolution for more than 40 years.
- Unfortunately, of course, Piltdown Man was a complete hoax. The cranium was from a modern human. The jaw had belonged to an orangutan. For good measure, some of the teeth had been filed down to make it look like it ate seeds. The bones had been treated with chemicals to make them look old. We are still not sure who perpetrated this fraud.

Lucy

- The search for big-brained human ancestors continued, but an important discovery in 1974 revolutionized paleoanthropology. Donald Johanson was looking for hominids in the Afar region of northeast Ethiopia when he noticed an interesting lump sticking out of the ground. This particular lump would turn the theory of human evolution upside down.

- The lump was determined to be an elbow joint; later excavation revealed a remarkable skeleton, about 40 percent complete. While Johanson and his team looked over the fossils, the Beatles song “Lucy in the Sky with Diamonds” played in the background; thus, Lucy got her name.
- Lucy’s formal name is *Australopithecus afarensis*, and she is dated to about 3.2 million years ago. Lucy had the head of an ape, and she did not have a large brain. What is important about Lucy, though, is that she walked like a human being: upright. It would appear that large brains did not evolve first; getting up on two legs was what drove humans on the path away from other apes.

Footprints in Africa

- Soon afterward the discovery of Lucy, the footprints of a hominid—either the same species as Lucy or closely related—were found in East Africa by Mary Leakey.
- The footprints are preserved in volcanic ash. After a brief rainfall, the ash was turned into a substance a bit like wet concrete. These hominids passed over the surface, which later dried out in the hot sun, preserving the trail.
- These footprints represent our ancestors (or at least closely related cousins) moving purposefully across the landscape. The prints record the passage of three individuals: possibly two males and a small female or a child following close behind. They date from 3.5 million years ago—perhaps the first record ever of a family outing.

Making and Using Tools

- It would appear that walking upright was what drove human evolution.
 - The theory is that walking upright frees the hands, and when the hands are free, we can make and use tools. This ability encourages the selection of better toolmakers, which means the adaptation of larger brains. Braininess follows walking, not the other way around.

- Walking on two legs must have a selective advantage, because walking upright has many severe disadvantages—the least of which is that it makes us slow.
- Also in the Afar region of Ethiopia, American paleontologist Tim White discovered the fossil *Australopithecus garhi*, which was either a descendant or relative of Lucy. This species was found associated with simple tools, dating to 2.6 to 2.5 million years ago. These tools were probably used for butchering animal bones to get to the marrow—which was high in calories and useful for supporting large brains.

Opportunistic Scavengers

- The idea of australopithecines butchering animals was taken to the extreme by Raymond Dart, an Australian anatomist and anthropologist. Dart was famous for his 1924 discovery of *Australopithecus africanus*, a young primate. Dart noted that the fossil's foramen magnum was under the skull, an indication of an upright walker. *Australopithecus africanus* was obviously more recent than Lucy; it existed 2.85 to 2 million years ago, in the Pliocene.
- Dart put forward an interesting hypothesis, called the killer ape theory, which suggested that the animal bones found at the site were used as weapons. He speculated that early hominids organized into vicious predatory groups. Dart believed that violent tendencies in the killer ape drove human evolution.
- Dart's theory of the killer ape is not supported by paleontological evidence. Australopithecines, like other bipedal apes, were, in all likelihood, more prey than predator.
- At best, the descendants of Lucy were probably opportunistic scavengers. They would get meat where they could, but probably only after every other animal on the landscape had taken its pick. They'd go after the marrow, breaking the bones open with their primitive tools.

- In the next lecture, we'll examine our own story, the story of the human branch of the upright apes: genus *Homo*. We'll also consider the flowering of human culture and its implications for Earth systems.

Suggested Reading

Johanson and Wong, *Lucy's Legacy*.

Sawyer, Deak, Sarmiento, and Milner, *The Last Human*.

Questions to Consider

1. Is it surprising to learn that mammals didn't diversify to form large creatures immediately (geologically speaking) after the extinction of the dinosaurs? Does this contradict the view of mammals being in some way superior to dinosaurs?
2. Given the nature of the fossil record and the scarcity of hominid fossils, how likely is it that we will ever find the true transitional form between chimps and humans?

The Conscious Earth

Lecture 36

Humans are a remarkable species. They are the only part of the biosphere to demonstrate self-awareness. In this lecture, we'll further explore the story of human evolution and discuss the early members of our immediate family. We'll find out about the first great explorer in genus *Homo*, contemplate when humans became self-aware and created culture, and introduce a new concept of geological periods. Finally, we'll take our biosphere beyond the Earth system and speculate about the possibilities of the future.

Handy Man

- Toolmaking is what distinguishes our branch of the primate family. Tool use and the development of tools are a vital part of the human story.
- *Australopithecus* used simple tools. The first member of our own genus, from about 2.4 million years ago, is named for the use of numerous and more advanced tools: *Homo habilis*, or “handy man.”
- It’s not just toolmaking and tool use that separated *H. habilis* from the australopithecines, however. *H. habilis* also had a brain of increased size—around 600 cubic centimeters (cc) compared to Lucy’s 200 cc. The upright apes, about 5 feet tall, had started to become brainy.
- *Homo habilis* still retained many apelike features, such as longer arms. *H. habilis* likely ate more meat, as well; analysis of molar teeth shows that they were sharpened, designed to shear meat, rather than the flat surfaces of Lucy’s teeth. Lucy was probably more adapted to eating fruit and berries than meat.
- *H. habilis* created more sophisticated tools, and it’s tempting to think that the larger brains in this group allowed them to hunt more

effectively as a team. *H. habilis*, though, was probably still prey for large cats, such as the saber-toothed *Dinofelis*. Our best assumption is that *H. habilis* was an effective scavenger—perhaps using group cooperation to scare away other scavengers or predators from a kill.

Homo Erectus

- During most of hominid evolution, there was more than one species of upright, bipedal ape. *Paranthropus boisei*, often known as “nutcracker man,” inhabited savannah woodlands. Males were around 4 feet, 3 inches, and weighed about 150 pounds. Because they had massive jaws and large molars, scientists speculate that they ate tough plants, roots, and nuts.
- One of the first species to demonstrate a humanlike body was *Homo erectus*, which means “upright man.” Early forms date to about 1.9 million years ago and are sometimes referred to as *Homo ergaster*, or “workman”—a reference to the more advanced tools used by this species.
- *H. ergaster* was tall, over 6 feet, with an apelike face and a brain of about 860 cc. It has been suggested that *H. ergaster* had a hairless body and sweat glands to regulate temperature. The development of sweat glands meant that *H. ergaster* did not have to pant, perhaps allowing the throat and breath to be used for speech.

Ability to Speak

- The ability to speak would be a distinct advantage. It would help cement social groups together; it would permit planning and coordination of hunting and foraging expeditions; and it would further success in securing mates.
- Brain casts of *H. ergaster* and *H. erectus* show development of a particular region of the brain called Broca’s area; in modern humans, this area controls speech.

- *Homo heidelbergensis*, fossils related to *H. erectus*, have been found to possess a hyoid bone. The hyoid bone supports the root of the tongue and is critical for making the whole range of vocalizations.

The First Explorer

- *Homo erectus* was the first of our family to get the urge to move on, out of Africa. The Sahara pump theory explains how and why. It proposes alternating wet and dry conditions in the Sahara.
- During wet times, grasslands developed, and animals would use this corridor to move into Arabia and along the coastline of the eastern Mediterranean, extending across Asia. *Homo erectus* was possibly one of the first species to take advantage of this green bridge.
- *Homo erectus* was a widely dispersed species; fossils have been found in South Africa, China, Java, and Western Europe. Even if *H. erectus* was not the first to get out of Africa, he certainly traveled widely.

Culture and Self-Awareness

- Early evidence of human culture was found in the Atapuerca Mountains in Spain, which contains the remains of the close relative of *H. erectus*: *H. heidelbergensis*.
- *H. heidelbergensis* had a fairly large brain, 1100 to 1400 cc, similar in size to the modern human's brain (about 1350 cc). This might explain why these hominids produced a highly complex array of tools. Some significant finds have been made in the cave Sima de los Huesos: 28 *H. heidelbergensis* skeletons were found there, with evidence that they were deliberately placed.
- Also found in the cave was a large and beautiful hand axe made of a red quartzite not from the local area. If this is evidence of a burial, it's extremely significant because such an event requires preparation of the dead and ritualistic offerings. It also demonstrates an ability to conceptualize an afterlife. From our imagination, our culture is born.

The Symbolic Language of Art

- Another indication of self-awareness and culture is in the symbolic language of art. The production of art appears to emerge almost spontaneously around 33,000 years ago. The most spectacular example of this early artwork is from southern France. In 1994, Jean-Marie Chauvet discovered a series of connected caves that were not only strewn with bones but also had walls decorated with spectacular paintings, dating to about 32,900 years ago.
- These and similar paintings at Lascaux in southwest France depict various animals in the landscape. Initially, it was thought that the artists depicted the animals they hunted, but butchered animals found in and around these caves don't match those shown on the cave walls.
- Other forms of artistic expression from this time have also been discovered, such as decorative beads and pendants; complex tools; and blades made from stone, bone, and antlers. These people also created such figurines as the Venus of Willendorf, dated to about 22,000 years ago and likely some sort of fertility symbol.

The “Human Revolution”

- What caused the sudden flowering of art and culture after some 200,000 years of evolution? Even if we allow for the more rapid changes of punctuated equilibrium, the explosion of consciousness is almost instantaneous. We have found no primitive precursors, no simpler forms of art leading up to the beautiful and complex forms in the French caves.
- Richard Klein at Stanford University suggests that a certain genetic mutation simply switched on the human brain. This would explain the sudden emergence of the cave paintings—an explosion of consciousness known as the “Human Revolution.”
- Klein speculates that this self-awareness is also why another group of hominids, the Neanderthals, was replaced by our species very

soon afterwards. We suddenly became self-aware and smarter and replaced the rest of our family.

- A discovery by Chris Henshilwood of the State University of New York at Stony Brook has challenged the theory of the Human Revolution. He found abstract designs, deliberately created, dating to about 70,000 years ago—well before the proposed flowering of the human mind.
- If these designs are art, culture and awareness were just like any other part of the human story: They developed slowly, in incremental stages, not in a sudden genetic mutation.

The Anthropocene Epoch

- Some scientists believe that we need to create a new geological period that accounts for the impact *Homo sapiens* has had on planet Earth: the Anthropocene.
- This geological period would be marked by large-scale human habitation or, perhaps, the presence in the geological record of plastics or stainless steel. Another marker would be the presence of radioisotopes from the testing of nuclear bombs, which already form an identifiable horizon in the sediments of the oceans today.

The Future of the Biosphere

- The average lifetime of a species is around 3 million years. Given this—and the fact that we live in a relatively dangerous universe at times—perhaps the future of the biosphere lies beyond the Earth system.
- If so, we need to find another place where we could transplant life from Earth. The problem is that we have not yet found a planet like ours, with an oxygen-rich atmosphere. That means we have to use the imagination that we evolved thousands of years ago to envision how we can use tools to alter planets to our needs. This kind of alteration is called terraforming, or planetary engineering.

- A likely candidate for this transformation is Mars. At one point, Mars had a warm atmosphere with liquid water on the surface. Mars also has some of the main components needed to successfully terraform a world: soil, atmosphere, and water (present as ice).
- Mars has carbon dioxide locked up at the poles; thus, warming the planet could start a positive feedback mechanism, releasing more carbon dioxide into the atmosphere and warming the planet further.
- The warmer Mars atmosphere would start to melt the ice deposits, returning oceans to the planet perhaps for the first time in billions of years. After that, we could add components of Earth's biosphere, starting with humble cyanobacteria, to start the planet on a path toward an oxygen-rich atmosphere.



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We are only starting to understand how Earth's complicated systems work to make our planet habitable, but we also need to think about transferring that knowledge to another planet to maintain our biosphere into the future.

Who Speaks for Earth? We Do

- It's exciting to think that our biosphere could transcend the Earth system that gave it birth and move out into the universe. Without doubt, these are interesting times for us and our planet.
- As a conscious element of the Earth system, we have to be its strongest advocate and pose the question that Carl Sagan asked: "Who speaks for Earth?" Sagan himself answered that question best: "We speak for Earth. Our obligation to survive is owed not just to ourselves but to that Cosmos, ancient and vast, from which we spring."

Suggested Reading

Lewis-Williams, *The Mind in the Cave*.

Sagan, *Pale Blue Dot*.

Sawyer, Deak, Sarmiento, and Milner, *The Last Human*.

Stony Brook University Medical Center, “‘Hobbit’ Skull Study Finds Hobbit Is Not Human.”

University of California—Santa Cruz, “Neanderthal Genome Yields Insights into Human Evolution and Evidence of Interbreeding with Modern Humans.”

Questions to Consider

1. Neanderthals had a brain that is similar in size to that of modern humans, and recently, evidence has been found that they, too, produced art. Is it possible that Neanderthals were as self-aware as we are?
2. What do you think our world would be like if we currently shared our planet with other conscious species of genus *Homo*?

Geologic Time

Note: Timespans listed below represent millions of years ago.

Eons	Eras	Periods
Phanerozoic: 542–present	Cenozoic: 65.5–present	Quaternary: 2.6–present
		Neogene: 23–2.6
		Paleogene: 65.5–23
	Mesozoic: 251–65.5	Cretaceous: 145.5–65.5
		Jurassic: 199.6–145.5
		Triassic: 251–199.6
	Paleozoic: 542–251	Permian: 299–251
		Carboniferous: 359.2–299
		Devonian: 416–359.2
		Silurian: 443.7–416
		Ordovician: 488.3–443.7
		Cambrian: 542–488.3
Precambrian Time: 4600–542	Proterozoic: 2500–542	Neoproterozoic: 1000–542
		Mesoproterozoic: 1600–1000
		Paleoproterozoic: 2500–1600
	Archean: 3800–2500	Neoarchean: 2800–2500
		Mesoarchean: 3200–2800
		Paleoarchean: 3600–3200
		Eoarchean: 4000–3600
	Hadean: 4600–4000	

Bibliography

Amos, Jonathan. "Fossil Tracks Record 'Oldest Land-Walkers.'" BBC News. January 6, 2010. <http://news.bbc.co.uk/2/hi/science/nature/8443879.stm> (accessed February 23, 2011). BBC article on the existence of possible tetrapod tracks that may predate *Tiktaalik*.

Armstrong, Howard, and Martin Brasier. *Microfossils*. Malden, MA: Blackwell, 2005. A useful university text on microfossils.

Bakker, Robert. *The Dinosaur Heresies: New Theories Unlocking the Mystery of the Dinosaurs and Their Extinction*. New York: Citadel, 2001. The classic book by Bob Bakker that paints dinosaurs as active and dynamic.

BBC News. "Oldest Fossil Fish Caught." November 4, 1999. <http://news.bbc.co.uk/2/hi/science/nature/504776.stm>. BBC article on the early chordates recovered from the Chengjiang fauna.

Beerling, D. J. *The Emerald Planet: How Plants Changed Earth's History*. Oxford: Oxford University Press, 2008. How the evolution of plants has had a serious impact on the Earth system.

Benton, Michael J. *When Life Nearly Died: The Greatest Mass Extinction of All Time*. London: Thames & Hudson, 2005. A well-written book describing the end-Permian extinction event.

Benton, Michael J., and David A. T. Harper. *Introduction to Paleobiology and the Fossil Record*. Hoboken, NJ: Wiley-Blackwell, 2009. A good general paleontology text.

Biello, David. "The Origin of Oxygen in Earth's Atmosphere." *Scientific American*. August 19, 2009. A summary of how we developed our oxygen-rich atmosphere.

California Institute of Technology. "Mass Extinction Linked to Ancient Climate Change, New Details Reveal." *ScienceDaily*. January 27, 2011. <http://www.sciencedaily.com/releases/2011/01/110127141703.htm> (accessed February 22, 2011). Article describing possible environmental/climatic causes of the Ordovician mass extinction.

Cowen, Richard. *History of Life*. 4th ed. Malden, MA: Blackwell, 2005. Well-written text on some of the main events in the evolving biosphere.

Denby, David. "Northern Lights: How Modern Life Emerged from Eighteenth-Century Edinburgh." *New Yorker*. October 11, 2004, 90. (Also available online at http://www.newyorker.com/archive/2004/10/11/041011crat_atlarge?currentPage=1.) An article about Edinburgh and the Scottish savants, a group that included James Hutton.

Ellis, Richard. *Sea Dragons: Predators of the Prehistoric Oceans*. Lawrence, KS: University of Kansas Press, 2005. A nicely illustrated introduction to the Mesozoic marine reptiles.

Emling, Shelley. *The Fossil Hunter: Dinosaurs, Evolution, and the Woman Whose Discoveries Changed the World*. New York: Palgrave Macmillan, 2009. The life and times of fossil hunter Mary Anning.

Erwin, Douglas, and James Valentine. *The Cambrian Explosion and the Construction of Animal Biodiversity*. Englewood, CO: Roberts & Company, 2010. A synthesis of the remarkable explosion of diversity around the base of the Cambrian period.

Fastovsky, David, and David Weishampel. *The Evolution and Extinction of the Dinosaurs*. 2nd ed. Cambridge: Cambridge University Press, 2005. A general text on dinosaurs.

Faure, Gunter, and Teresa Mensing. *Introduction to Planetary Science: The Geological Perspective*. Dordrecht: Springer, 2007. A university-level text; a well-illustrated and well-written guide to planetary sciences.

Fedonkin, Mikhail, James Gehling, Kathleen Grey, Guy Narbonne, and Patricia Vickers-Rich. *The Rise of Animals: Evolution and Diversification of the Kingdom Animalia*. Baltimore, MD: Johns Hopkins University Press, 2008. A great introduction to the world of the Ediacaran animals.

Foote, Michael J., and Arnold Miller. *Principles of Paleontology*. 3rd ed. New York: Freeman, 2007. A more advanced, technical text based on the classic book by David Raup and Steven Stanley.

Fortey, Richard. *Trilobite: Eyewitness to Evolution*. New York: Vintage, 2001. Richard Fortey's views of the Cambrian explosion and evolution in the Paleozoic through the eyes of the trilobites.

Freie Universitaet Berlin. "Prolonged Climatic Stress Main Reason for Mass Extinction 65 Million Years Ago, Paleontologist Says." *ScienceDaily*. March 27, 2010. <http://www.sciencedaily.com/releases/2010/03/100326124654.htm> (accessed February 23, 2011). An article that favors climate change as an explanation for the K-P extinction.

Gee, Henry, ed. *Shaking the Tree: Readings from Nature in the History of Life*. Chicago: University of Chicago Press, 2000. A collection of review articles from the journal *Nature* that cover some of the major issues in modern paleontology.

Gould, Stephen Jay, ed. *The Book of Life: An Illustrated History of the Evolution of Life on Earth*. 2nd ed. New York: Norton, 2001. A well-illustrated book, a little dated now, but still providing a great introduction to some of the highlights in life's history.

———. *Wonderful Life: The Burgess Shale and the Nature of History*. New York: Norton, 1990. An old book but still a classic that was probably responsible for bringing the Burgess Shale back into public consciousness.

Hallam, Anthony. *Catastrophes and Lesser Calamities: The Causes of Mass Extinctions*. Oxford: Oxford University Press, 2005. An examination and investigation of the times when Earth's biosphere has suffered a downturn.

Hoffman, Paul. *Snowball Earth*. <http://www.snowballearth.org>. Paul Hoffman's website regarding the Snowball Earth hypothesis.

Imperial College London. "Asteroid Killed off the Dinosaurs, Says International Scientific Panel." *ScienceDaily*. March 4, 2010. <http://www.sciencedaily.com/releases/2010/03/100304142242.htm> (accessed February 23, 2011). Forty-one scientists agree that impact was the cause of the K-P extinction.

Johanson, Donald, and Kate Wong. *Lucy's Legacy: The Quest for Human Origins*. New York: Three Rivers Press, 2010. A description of the human family from the discoverer of Lucy.

Kemp, T. S. *The Origin and Evolution of Mammals*. Oxford: Oxford University Press, 2005. A text on the evolution of the mammals.

Kious, W. Jacquelyne, and Robert Tilling. *This Dynamic Earth: The Story of Plate Tectonics*. Denver: U.S. Geological Survey, 1996. (Also available online at <http://pubs.usgs.gov/gip/dynamic/dynamic.html>; accessed February 23, 2011.) A concise, well-illustrated introduction to plate tectonics.

Knoll, Andrew. *Life on a Young Planet: The First Three Billion Years of Evolution on Earth*. Princeton, NJ: Princeton University Press, 2004. The origin of life and the first fossils, as described by Andrew Knoll, a Harvard paleontologist.

Lane, Nick. *Life Ascending: The Ten Great Inventions of Evolution*. New York: Norton, 2010. A well-written book that investigates some of the great biological inventions of life.

———. *Oxygen: The Molecule That Made the World*. Oxford: Oxford University Press, 2004. An easy-to-read book describing the importance that oxygen has had on the evolving biosphere and the effects it may have today on human health.

Laurin, Michel. *How Vertebrates Left the Water*. Berkeley: University of California Press, 2010. Summarizes some of the key events in the development of terrestrial tetrapods.

Levin, Harold. *The Earth through Time*. 9th ed. Hoboken, NJ: Wiley, 2010. A general text on Earth history.

Lewis-Williams, J. David. *The Mind in the Cave: Consciousness and the Origins of Art*. London: Thames & Hudson, 2004. An investigation into the interpretation of cave art.

Lindsey, Rebecca. "Ancient Crystals Suggest Earlier Ocean." *NASA Earth Observatory*. March 1, 2006. <http://earthobservatory.nasa.gov/Features/Zircon/zircon.php>. A NASA article concerning the Jack Hills zircons, possibly the oldest Earth-formed features.

Lovelock, James. *The Ages of Gaia*. New York: Norton, 1995. An easy-to-read, general introduction to Lovelock's Gaia hypothesis.

———. Personal website. <http://www.jameslovelock.org/page0.html>. Links to papers, articles, and speeches by Lovelock.

Martin, Anthony. *Introduction to the Study of Dinosaurs*. Malden, MA: Blackwell, 2006. A general text on dinosaurs.

Martin, Paul. *Twilight of the Mammoths: Ice Age Extinctions and the Rewilding of America (Organisms and Environments)*. Berkeley: University of California Press, 2007. An investigation into the "overkill hypothesis" of the extinction of the megafauna.

McCoy, Roger. *Ending in Ice: The Revolutionary Idea and Tragic Expedition of Alfred Wegener*. Oxford: Oxford University Press, 2006. Describes Wegener's struggles with the scientific community and the challenges faced by 20th-century explorers in the Arctic.

Morris, Simon Conway. *The Crucible of Creation: The Burgess Shale and the Rise of Animals*. Oxford: Oxford University Press, 2000. A well-written,

easy-to-read book by an author who has considerable experience working with fossils from the Burgess Shale.

NASA/Goddard Space Flight Center. "Explosions in Space May Have Initiated Ancient Extinction on Earth." *ScienceDaily*. April 11, 2005. <http://www.sciencedaily.com/releases/2005/04/050411101721.htm> (accessed February 22, 2011). Article describing the possible gamma ray burst cause of the Ordovician mass extinction.

Oregon State University. "Bird-from-Dinosaur Theory of Evolution Challenged: Was It the Other Way Around?" *ScienceDaily*. February 10, 2010. <http://www.sciencedaily.com/releases/2010/02/100209183335.htm> (accessed February 23, 2011). An article addressing the question: Did the birds really evolve from dinosaurs?

Ricardo, Alonso, and Jack Szostak. "The Origin of Life on Earth: Fresh Clues Hint at How the First Living Organisms Arose from Inanimate Matter." *Scientific American*. August 19, 2009. An investigation into the manner in which life may have developed from chemicals present in the early Earth system.

Ruddiman, William F. *Earth's Climate: Past and Future*. New York: Freeman, 2007. A general text on past and current climate change.

Sagan, Carl. *Pale Blue Dot: A Vision of the Human Future in Space*. New York: Ballantine Books, 1997. An exploration of past astronomical discoveries and possible futures.

Sawyer, G. J., Viktor Deak, Esteban Sarmiento, and Richard Milner. *The Last Human: A Guide to Twenty-Two Species of Extinct Humans*. New Haven, CT: Yale University Press, 2007. Great illustrations of our human ancestors.

Schopf, J. William, ed. *Life's Origin: The Beginnings of Biological Evolution*. Berkeley: University of California Press, 2002. A book describing the controversial topic of the origin of life; the editor has been highly involved with the study of life on the early Earth.

Shubin, Neil. *Your Inner Fish: A Journey into the 3.5-Billion-Year History of the Human Body*. New York: Pantheon Books, 2008. Neil Shubin examines how the human body evolved to its present state.

Skinner, Brian, Stephen Porter, and Daniel Botkin. *The Blue Planet: An Introduction to Earth System Science*. 3rd ed. Hoboken, NJ: Wiley, 2011. A general Earth science textbook with an Earth system science theme.

Smithsonian Tropical Research Institute. “Sex in the Caribbean: Environmental Change Drives Evolutionary Change, Eventually.” *ScienceDaily*. October 13, 2009. <http://www.sciencedaily.com/releases/2009/07/090728223020.htm> (accessed February 23, 2011). Describes some of the consequences for marine creatures of the closure of the Isthmus of Panama.

Stony Brook University Medical Center. “‘Hobbit’ Skull Study Finds Hobbit Is Not Human.” *ScienceDaily*. January 21, 2009. <http://www.sciencedaily.com/releases/2009/01/090120144508.htm> (accessed February 23, 2011). An article examining the question: Was *Homo floresiensis* a separate member of the human family?

University of California—Riverside. “Oxygen-Free Early Oceans Likely Delayed Rise of Life on Planet.” *ScienceDaily*. January 10, 2011. <http://www.sciencedaily.com/releases/2011/01/110110151016.htm> (accessed February 22, 2011). Describes the state of the oceans prior to abundant oxygen.

University of California—Santa Cruz. “Neanderthal Genome Yields Insights into Human Evolution and Evidence of Interbreeding with Modern Humans.” *ScienceDaily*. May 6, 2010. <http://www.sciencedaily.com/releases/2010/05/100506141549.htm> (accessed February 23, 2011). Did modern humans and Neanderthals interbreed?

University of Manchester. “Prehistoric Birds Were Poor Flyers, Research Shows.” *ScienceDaily*. May 26, 2010. <http://www.sciencedaily.com/releases/2010/05/100526100612.htm> (accessed February 23, 2011). Describes the nature of “dinosaur feathers” and research to address the question of whether early birds were poor flyers.

Varricchio, Louis. *Inconstant Moon: Discovery and Controversy on the Way to the Moon*. Philadelphia: Xlibris Corp., 2006. Some of the missions and controversy surrounding the exploration of the Moon.

Walker, Gabrielle. *Snowball Earth: The Story of a Maverick Scientist and His Theory of the Global Catastrophe That Spawned Life as We Know It*. New York: Three Rivers Press, 2004. The story of Paul Hoffman and the development of the Snowball Earth hypothesis.

Weidenbach, Kristin. *Rock Star: The Story of Reg Sprigg—An Outback Legend*. Hindmarsh, S. Aust.: East Street Publications, 2008. Describes the life and times of one of Australia's pioneering geologists and the discoverer of the Australian Ediacaran animals.

Wicander, Reed, and James Monroe. *Historical Geology*. 5th ed. Belmont, CA: Thomson-Brooks/Cole, 2007. A general text on paleontology and Earth history.

Winchester, Simon. *The Map That Changed the World: William Smith and the Birth of Modern Geology*. New York: HarperCollins, 2001. A very readable book about William Smith and the challenges he faced in publishing his famous geological map.

Yale University. "Fossil Find Fills in Picture of Ancient Marine Life." *ScienceDaily*. May 14, 2010. <http://www.sciencedaily.com/releases/2010/05/100513123829.htm> (accessed February 22, 2011). An article describing Burgess Shale-type animals found outside of the Cambrian.